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3rd Tech DeltaSphere-3000® Laser 3D Scene Digitizer Infrared Laser Scanner Hazard Analysis

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Abstract

A laser hazard analysis and safety assessment was performed for the 3rd Tech model DeltaSphere-3000® Laser 3D Scene Digitizer, infrared laser scanner model based on the 2000 version of the American National Standard Institute's Standard Z136.1, *for the Safe Use of Lasers*. The portable scanner system is used in the Robotic Manufacturing Science and Engineering Laboratory (RMSEL). This scanning system had been proposed to be a demonstrator for a new application. The manufacture lists the Nominal Ocular Hazard Distance (NOHD) as less than 2 meters. It was necessary that SNL validate this NOHD prior to its use as a demonstrator involving the general public. A formal laser hazard analysis is presented for the typical mode of operation for the current configuration as well as a possible modified mode and alternative configuration.

Summary

For the "worst case" (slowest mirror rotation rate) the small source Nominal Ocular Hazard Distance (NOHD) for the 3rd Tech model DeltaSphere-3000 in its current configuration (4 revolutions per second with a sample density of 13.3 samples per degree) is approximately 188 centimeters, which is greater than the extended source to small source crossover distance. The DeltaSphere-3000 in its current configuration presents a Class 3a Laser System Hazard (with an embedded Class 3b laser) and laser safety eyewear, is required to be worn by personnel inside this hazard distance.

Ocular Hazard Distance (Worst Case)

Mirror Rotation (Rev/Sec)	Sample Density (Samples/Degree)	NOHD (cm)	Configuration
4	**13.3**	**~188**	**Current**
4	13.3	<133	Modified
8	10*	~123	Alternate

*Requires 3rd Tech to preset the default Sample Density through software control.

The Optical Density required of laser safety eyewear (for full protection) at the exit of the laser, in its *current configuration*, which also is adequate for all radial distances inside the ocular hazard zone is:

$$\mathbf{OD_{min} = 1.13 \ @ \ 780\ nm}$$

For both the "modified" and the "alternate" configurations of the DeltaSphere-3000, the *small source* NOHD is less than the *extended source* to *small source* crossover distance. The *extended source correction factor* can be applicable to these configurations. Although; with the application of *extended source correction factor* to the AEL, both the "modified" and the "alternate" configuration would present a Class 1 laser system hazard, it would still be prudent to maintain a "personnel exclusion zone", about the scanner, equaled to the *small source* NOHD listed above.

Modification to the Current Configuration (ND0.1 Filter)

The inclusion of a neutral density filter in the emitted beam path reduces the small source NOHD to where this distance is shorter than the extended source to small source crossover distance. The radiant energy transmitted through the limiting aperture is less than the appropriate AEL-s (the extended source AEL for radial distances from 10 centimeters to the crossover distance (approximately 149 centimeters) and the small source AEL for radial distances greater than 149 centimeters.

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Figure 1

The DeltaSphere-3000 and its carrying case

I. Introduction

The manufacturer, 3rd Tech, makes the claim that the DeltaSphere-3000 is a portable, long range, high precision and high-speed 3D scene digitizer, which incorporates an infrared diode laser scanner. The DeltaSphere-3000 is mounted such as to allow it to sweep horizontally while the rotating mirror makes vertical scans. The rangefinder system is computer controlled. The DeltaSphere-3000 user manual warns against personnel exposure to the laser beam inside of two meters from the laser's exit.

II. Laser Parameters

Model:	DeltaSphere-3000
Embedded Laser Hazard Class:	3b
Laser Wavelength:	780 nm
Embedded Diode Laser Power:	8 mw
Beam diameter:	2.5 mm
Beam divergence:	0.5 mr
Distance (Laser to Mirror):	180 mm
Mirror Rotation Rates	4-16 revolution per second*
Minimum Mirror rotation rate:	4 revolutions per second†
Incremental Sweep:	1 sample per mirror revolution
Sample Density (preset):	13.3 samples per degree

Notes:
*The current maximum mirror rotation rate is 16 revolutions per second.
†The laser diode is interlocked to the rotating mirror to "cut off" laser operation if the mirror rotation rate falls below 4 revolutions per second.

III. System Configuration

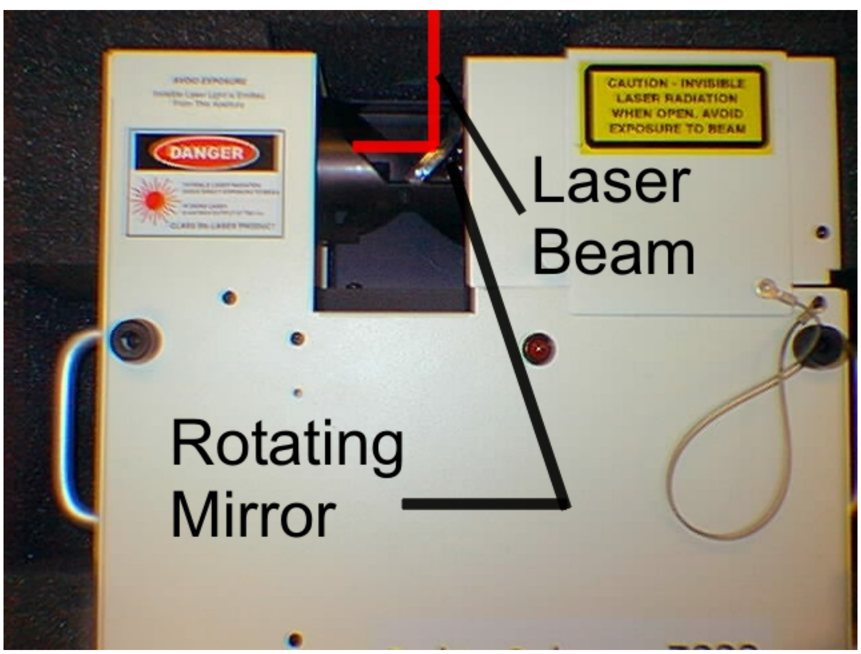


Figure 2

Laser beam path and rotating mirror.

A. **Overview**

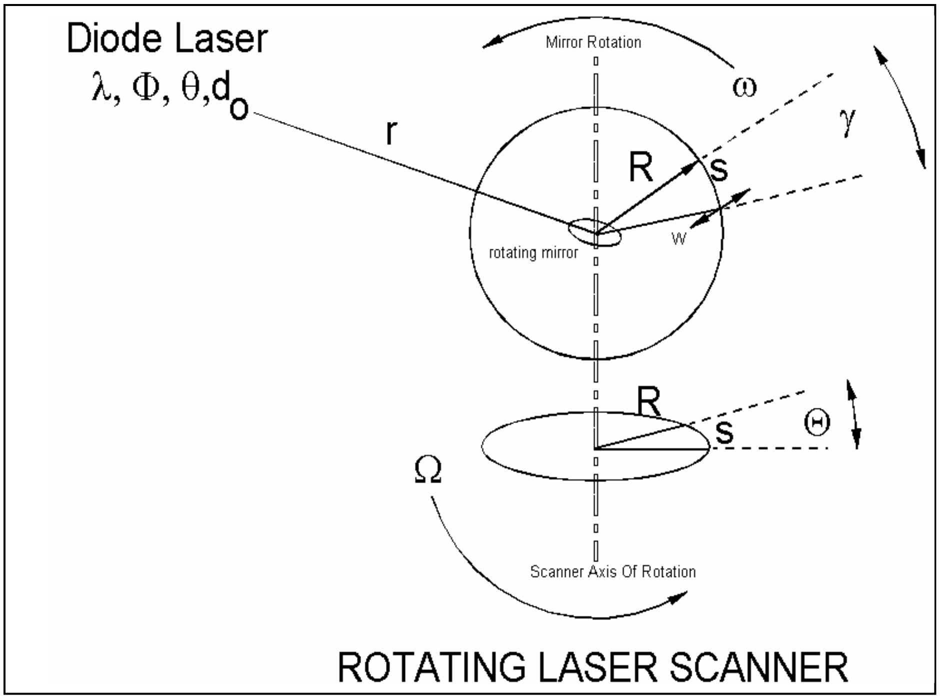


Figure 3

Laser scanner configuration.

The CW diode laser output is directed to the rotating mirror, which scans the laser beam through a complete 360-degree arc. The **scan rate** (ω) is equal to the mirror rotation rate. The scanner rotates one angular increment (Θ) for each mirror rotation (scan), at the average **scanner sweep** (rotation) **rate** (Ω). The interactive beam returns collinearly and is split off and processed by the scanner's electronic system.

B. **Beam Divergence**

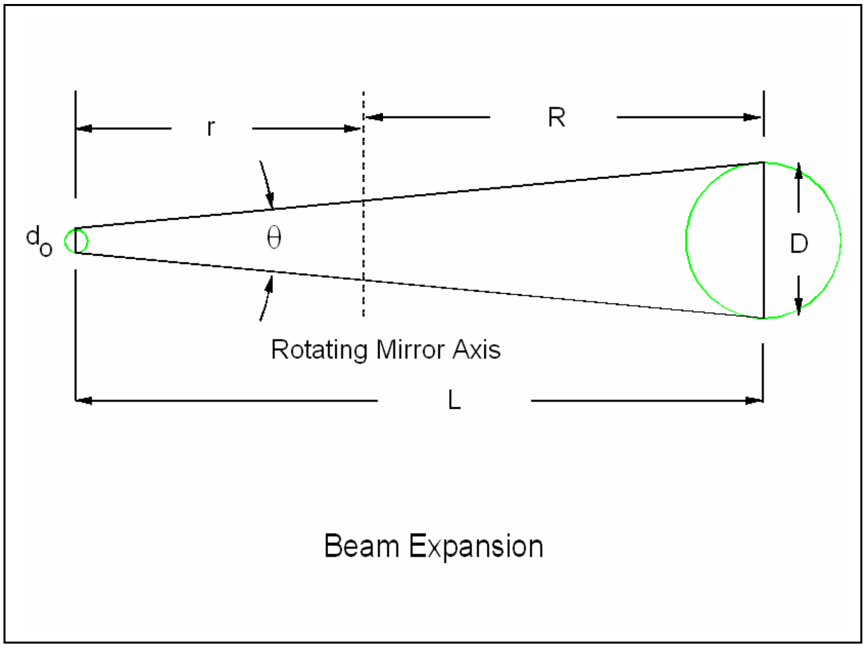


Figure 4

Laser spot size expansion as the beam travels from the source.

The laser beam cross section expands (diverges as a natural consequence of the laser systems physical geometry) as it propagates away from the laser. The size of the laser beam diameter (*D*) is a function of the **beam diameter** (d_o) at the laser exit, the **beam divergence** angle (θ) and the **distance** (*L*) from the laser. The distance (*L*) from the laser source is the sum of the **distance from the laser to the rotating mirror** (*r*) and the **radial distance** (*R*) from the rotating mirror and can be expressed as function of the radial distance as follows.

$$D = f(R, r, d_o, \theta)$$

$$D = d_o + \theta(r + R)$$

C. **Irradiance**

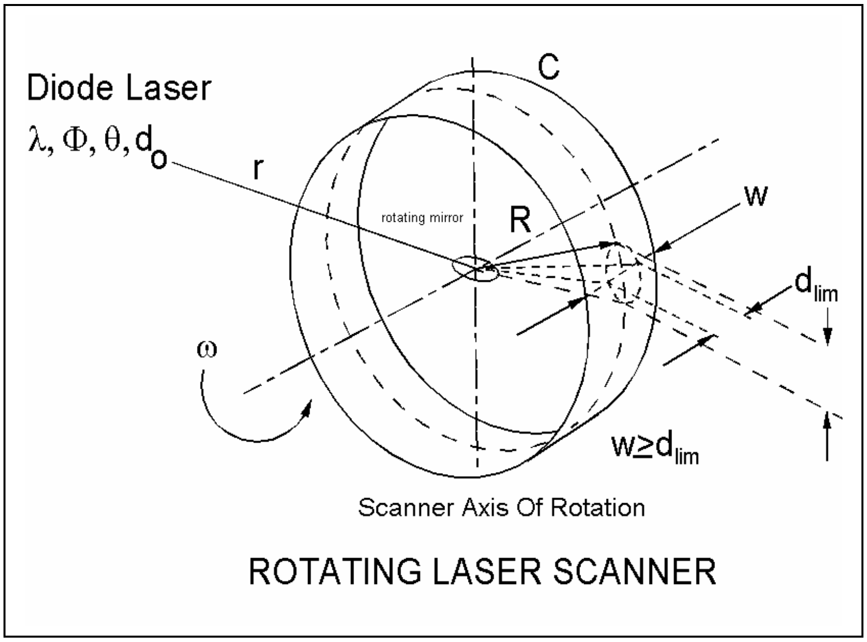


Figure 5

The rotating laser beam sweeps an area proportional to the radial distance from the mirror.

The **irradiance** or **power density** (H) of the emitted beam is the **average radiant power** (Φ) distributed over the **beam (scanned) area** (A). The area is a function of the radial distance from the rotating mirror and is the product of the **beam width** (w), which is equal to the **beam diameter** (D) for a circular beam and the circumference of the circle scanned at the **radial distance** (R) from the rotating mirror.

$$H = \frac{\Phi}{A}$$

It is assumed that the transmitted laser beam is circular and is a function of the radial distance from the rotating mirror such that:

$$w = D$$

$$w = d_o + \theta(r + R)$$

The average irradiance can be expressed as a function of the radial distance from the rotating mirror.

$$H = \frac{\Phi}{wC}$$

$$H = \frac{\Phi}{\left(d_o + \theta\left[r + R\right]\ \right)\ \cdot \left(2\pi R\right)} \quad {}^{w}\!/_{cm^2} \qquad \text{for}$$

$$w \geq d_{\lim}$$

D. **Radiant Exposure Time** (through an aperture)

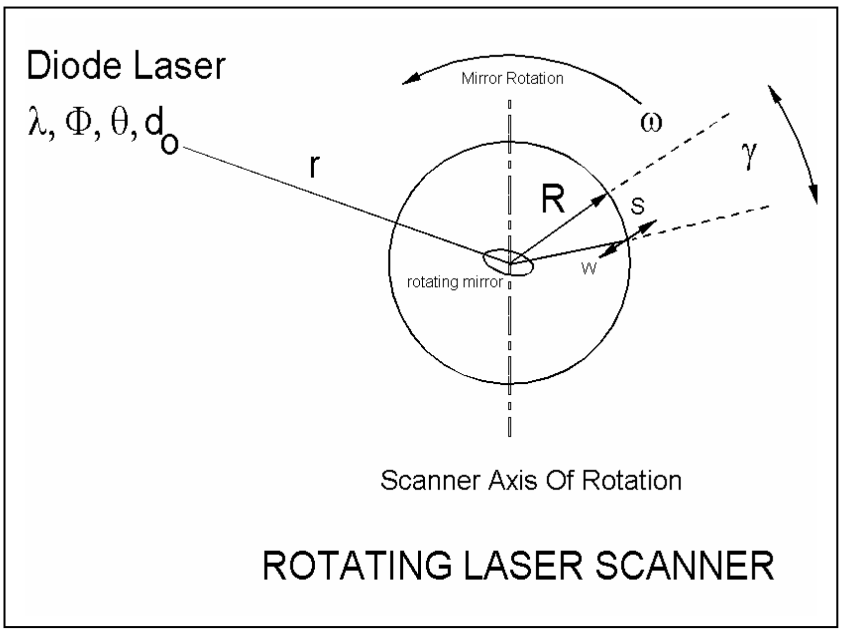


Figure 6

Single scan of the rotating mirror.

Let the laser beam, at some **radial distance** (R), sweep past an **aperture** (s). The **exposure time** (t) across the aperture is a function of the **radial distance** from the rotating mirror (R), the **rotation rate** (ω), and the aperture size (s).

The exposure time of the pulse event transmitted through an aperture at the radial distance (R) can be expressed as:

$$t = \left(\frac{1}{\omega}\right) \cdot \left(\frac{s}{2\pi R}\right)$$

$$t = \frac{s}{2\pi R \cdot \omega} \quad \text{sec}$$

Where;

t :	Pulse exposure time (sec).
ω :	Mirror rotation rate (rev/sec).
R :	Radial distance (cm).
s :	Aperture (cm)

The radiant beam intensity versus transit time across the aperture would appear as a pulse event, where the radiance transmitted through the aperture would appear similar as depicted in figure 7.

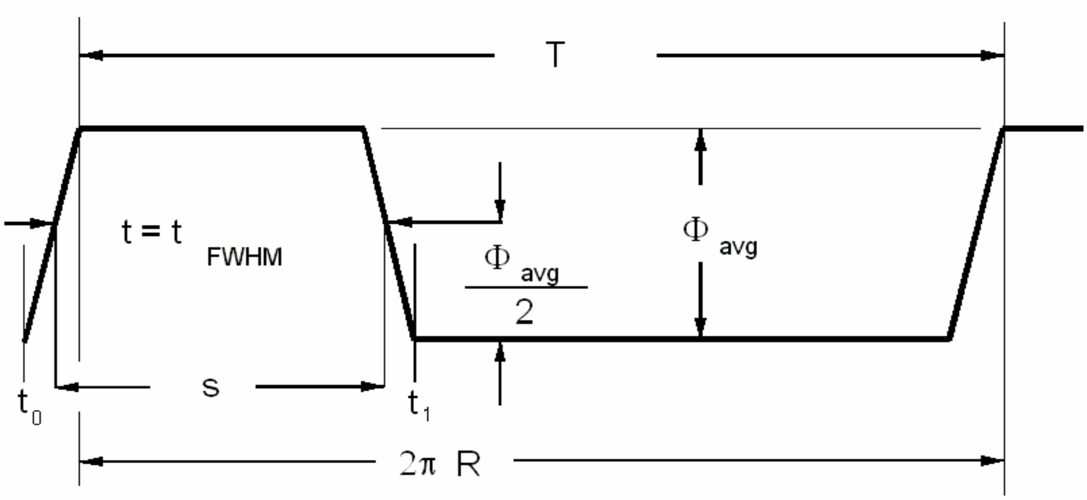


Figure 7

The transmitted radiant power (intensity versus time) through the aperture can be expressed as a function of the aperture size, the radial distance and the mirror rotation rate.

The exposure time (t) is the time between the "half power" points $\left(\Phi_{avg}/2\right)$ of the transmitted radiance and represents the pulse width of the pulse event.

$$t = t_{FWHM}$$

Multiple scans of the rotating CW laser beam give rise to a multiple pulse exposure where the **pulse period** (T) is a function of the mirror rotation rate (ω).

$$T = \frac{1}{\omega}$$

The time for a single mirror scan is related to the mirror rotation rate.

$$T_{scan} = \frac{1}{\omega}$$

E. **Radiant Energy** (Transmitted through the aperture at "R")

The **radiant energy** (Q) transmitted through the aperture (s) scanned by the rotating laser beam is proportional to the ratio of the incident radiant power to the mirror rotation rate and the ratio of the area of the transmitted beam to the area of the scan, where the incident radiant power is assumed to be spatially as well as temporally uniform.

$$Q_s = \left(\frac{\Phi}{\omega}\right) \cdot \left(\frac{A_\tau}{A_{scan}}\right)$$

Where;

Q_s:	Radiant energy transmitted through the aperture (cm).
Φ:	Incident radiant laser beam power (watts).
ω:	Mirror rotation rate (revolutions per second).
A_τ:	Area of the transmitted beam (cm^2).
A_{scan}:	Area of the scan (cm^2).

The radiant energy transmitted through the aperture can be expressed as a function of the radial distance from the rotating mirror.

The radiant energy transmitted through the aperture can be expressed as:

$$Q_s = \left(\frac{\Phi_{avg}}{\omega}\right) \cdot \left[\frac{A_\tau}{A_{scan}}\right]$$

$$Q_s = \left(\frac{\Phi_{avg}}{\omega}\right) \cdot \left[\frac{A_\tau}{C \cdot w}\right] \qquad \text{For: } w \geq s$$

Where;

Q_s :	Radiant energy transmitted through the aperture (cm).
Φ_{avg} :	Average incident radiant laser beam power (watts).
ω :	Mirror rotation rate (revolutions per second).
A_τ :	Area of beam transmitted through the aperture (cm^2).
C :	Scan circumference (cm).
w :	Laser beam width at the aperture (cm).

The radiant energy can also be expressed as a function of the radial distance from the rotating mirror.

$$Q_s = \left(\frac{\Phi_{avg}}{\omega}\right) \cdot \left[\frac{A_\tau}{(2\pi \cdot R) \cdot w}\right]$$

$$Q_s = \left(\frac{\Phi_{avg}}{\omega}\right) \cdot \left[\frac{A_\tau}{(2\pi \cdot R) \cdot (d_o + \theta(r + R))}\right]$$

Where;

R :	Radial distance from the rotating mirror (cm).
d_o :	Exit diameter at the laser (cm).
r :	Distance from laser to rotating mirror (cm).
θ :	Beam divergence (radians).

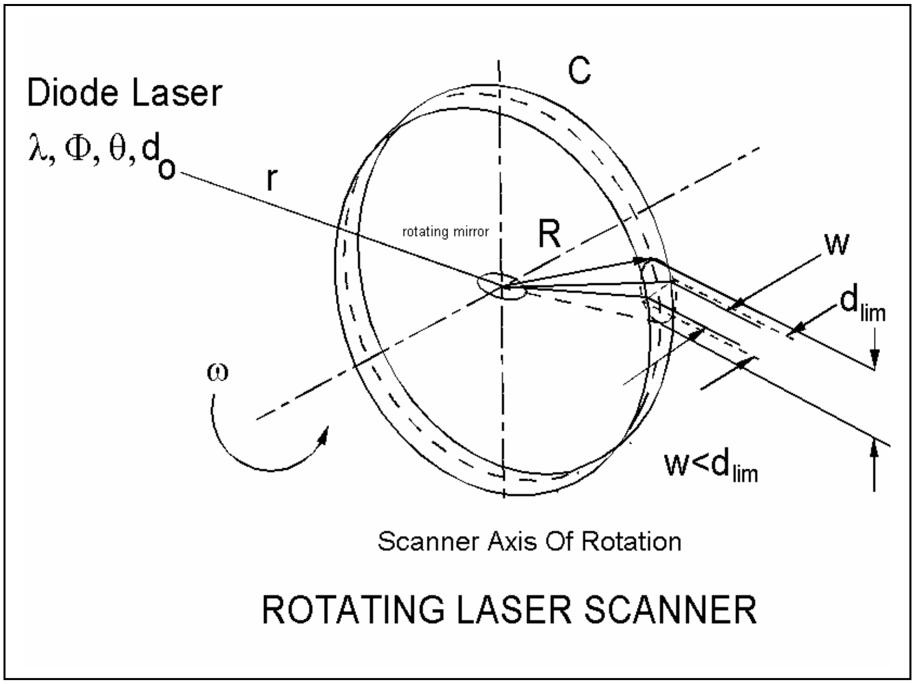


Figure 8

Scan area for beam widths less than the limiting aperture.

For the condition where the aperture (*s*) is larger than the beam width (*w*) the laser power transmitted through the aperture is equal to the incident laser power at the aperture. The transmitted radiant energy can be expressed as the ratio of the laser power to the mirror rotation rate and the ratio of the transmitted area to scan area. The radiant energy transmitted through the aperture is a function of the radial distance from the rotating mirror. This can be approximated as the ratio of the aperture diameter to the scan circumference (first order approximation or one dimensional approximation).

$$Q_s \approx \left(\frac{\Phi}{\omega}\right)\left[\frac{S}{(2\pi \cdot R)}\right] \quad J \qquad \text{For:} \quad w \le s$$

F. **Scanner Rotation**

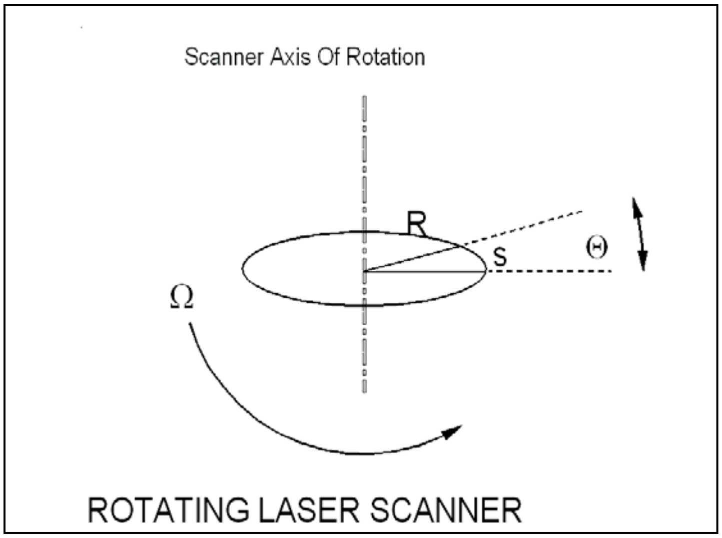


Figure 9

The schematic of the Laser Scanner Rotation.

As the 3rd Tech DeltaSphere-3000 is swept horizontally, the length of the arc (*s*) is a function of the radial distance (*R*) and the angular displacement (Θ).

$$S = \Theta R$$

The average rotation rate can be expressed as:

$$\Omega = \frac{\Theta}{T}$$

Where;

Ω :	Average rotation (scanner sweep) rate
Θ :	Angular increment.
T :	Time for sweep increment

The scanner completes one scan for each revolution of the rotating mirror. The scanner sweeps one rotation increment for each mirror rotation.

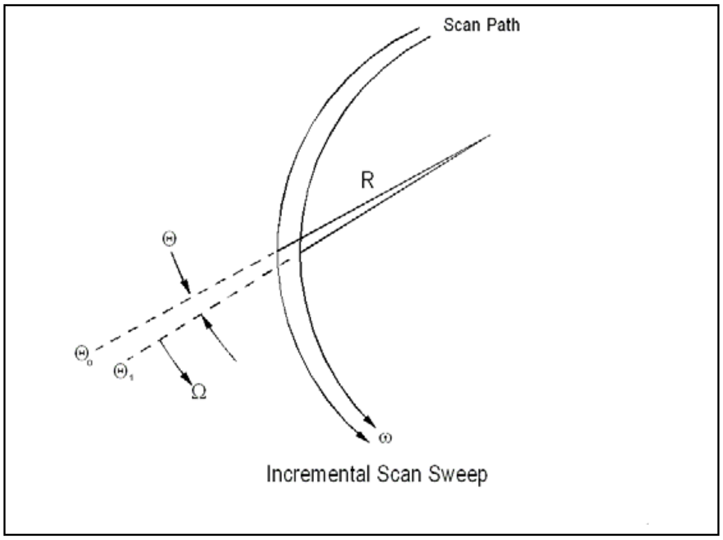


Figure 10

Depicts incremental scanner rotation, where Θ_0 is the initial position and increments to Θ_1 after the first mirror-scan at the mirror rotation rate, ω.

The **incremental scan rotation angle** (Θ) can be expressed in terms of the inverse of the **sample density**. The number of scans (*N*) per degree is referred to as the **sample density**. The angular separation or sweep increment (Θ) between vertical scans can then be expressed as:

$$\Theta = \left(\frac{\deg}{N}\right) \cdot \left(\frac{\pi \quad radians}{180^\circ}\right)$$

For the DeltaSphere-3000 Laser 3D Scene Digitizer IR laser scanner the sample density is preset to 13.3 samples per degree by 3rd Tech.

$$\Theta = \left(\frac{\deg}{13.3}\right) \cdot \left(\frac{\pi \quad radians}{180^\circ}\right)$$

The angular sweep increment is for the default configuration is:

$$\Theta = 1.312 \times 10^{-3} \quad radians$$

The arc swept between mirror scans is a function of the radial distance from the rotating mirror and can be expressed as follows.

$$S = \Theta \cdot R$$

$$S = \left(1.31 \times 10^{-3}\right) R$$

The average scanner **sweep rate** (Ω) can be expressed as a function of the scanner **angular rotation increment** (Θ) and the **time** (T) between scanner angular rotation increments, which in turn can be related to the **mirror rotation rate** (ω) as follows.

The average scanner sweep rate in **terms of radians** can be expressed as follows:

$$\Omega = \frac{\Theta}{\mathrm{T}} \ \mathit{radians}/\mathrm{sec}$$

$$\Omega = \Theta \cdot \omega \ \mathit{radians}/\mathrm{sec}$$

$$\Omega = \left(1.312 \times 10^{-3} \ \mathit{radians}\right)\left(4 \ \ \mathrm{sec}^{-1}\right)$$

$$\Omega = 5.25 \times 10^{-3} \ \mathit{radians}/\mathrm{sec}$$

The average scanner sweep rate in **terms of degrees** can be expressed as follows:

$$\Omega = \left(5.25 \times 10^{-3} \ \mathit{radians}/\mathrm{sec}\right)\left(\frac{180^{\circ}}{\pi}\right)$$

$$\Omega = 0.3 \ \ \mathrm{deg}/\mathrm{sec}$$

IV. <u>Hazard Analysis</u>

A. **Limiting aperture**

The **limiting aperture** $(d_{\lim})$ is used as a normalization factor in the performance of the laser hazard analysis. The limiting aperture for the NIR (780 nm) diode laser incorporated in the DeltaSphere-3000® laser scanner is given as: **7 mm** [*ANSI Std. Z136.1-2000 (Table 8)*].

Hence defining the aperture as the limiting aperture:

$$s \equiv d_{\lim}$$

$$d_{\lim} = 0.7 \ cm$$

B. **Radiant Energy** (through the limiting aperture)

The radiant energy $(Q_{\lim})$ transmitted through the limiting aperture was shown to be approximately in direct proportion to the ratio of the limiting aperture to the circumference of the mirror scan (page 16). This one-dimensional approach approximates the transmitted radiant energy (through the limiting aperture at a specific radial distance) as being proportional to the ratio of the diameter of the limiting aperture to the circumference of the mirror scan. The two-dimensional approach relates this transmitted radiant energy to the ratio of the transmitted beam area through the limiting aperture to the area of the scan swept by the rotating mirror (page 14).

One-Dimensional Approximation versus the Two-Dimensional Method

The **one-dimensional** (1D) approach is simpler and less complicated to evaluate than the two dimensional approach; but it will yield a higher estimated value for the radiant energy transmitted through the limiting aperture at a specific radial distance than the two dimensional approach. This produces an estimated transmitted radiant energy with a **conservative safety bias**, which is carried through in the subsequent laser hazard analysis.

The one-dimensional approach to the determination of the transmitted radiant energy will be presented first in order to provide for a general level of the radiant energy transmitted through the limiting aperture.

The **two-dimensional** (2D) approach is a more complicated method of estimating the radiant energy transmitted through the limiting aperture and is presented later to provide for a more accurate evaluation of the transmitted radiant energy at certain specific radial distances necessary in the laser hazard analysis.

1. **One-Dimensional Method (ratio of diameter to the circumference)**

The one-dimensional method (1D) for estimating the radiant energy transmitted through the limiting aperture can be approximated as a function of the **laser power** (Φ) **radial distance** (R) and the **mirror rotation rate** (ω) and can be expressed as (refer to page 16).

$$Q_{\lim} \approx \Phi \left[\frac{d_{\lim}}{2\pi R \cdot \omega} \right] \quad J \qquad \text{For: } w \le d_{\lim}$$

The radial distance, where the laser beam width (w) is equal to the limiting aperture ($d_{\lim}$) can be determined as follows.

$$d_{\lim} = d_o + \theta(r + R) \qquad \text{(Refer to page 11)}$$

$$R = \frac{d_{\lim} - d_o}{\theta} - r$$

$$R = \frac{0.7cm - 0.25\ cm}{0.5 \times 10^{-3}} - 18\ cm$$

$$R = 882\ \ cm \qquad \text{Where; } w = d_{\lim}$$

For radial distances less than 882 centimeters the radiant energy (Q_{lim}) transmitted through the limiting aperture for each revolution of the rotating mirror can be estimated as follows.

$$Q_{\lim_{1D}} = \Phi \cdot t$$

$$Q_{\lim_{1D}} \approx \Phi \left[\frac{d_{\lim}}{2\pi R \cdot \omega} \right] \quad J \qquad \text{(Refer to page 16)}$$

Red Plexiglas Window

The transmission factor (τ) of the red Plexiglas exit window (DeltaSphere-3000) was measured, by a Cary® 500 Spectrophotometer, as: **93.25 percent at 780 nm**. The incident radiant (Φ) power used in the subsequent hazard analysis is the embedded diode laser output power corrected by this window transmission factor.

$$\Phi = \tau \cdot \Phi_{embedded\ \ laser}$$

$$\Phi = (0.9325) \cdot \left(8 \times 10^{-3}\, watts\right)$$

$$\Phi = 7.46 \times 10^{-3}\, watts$$

The radiant power was measured (6.88 mw) at the window exit with an Ophir® Model 2A-SH power head (60 μw to 2 watts CW @ ± 3% accuracy error) and an Ophir® Model NOVA digital display (calibrated in the NIR) combined system accuracy error ± 4% . Since the measured value of the radiant power was less than the calculated value for the radiant power at exit, the higher calculated value is used throughout the laser hazard analysis to maintain a conservative safety bias.

Transmitted Radiant Energy (1D)

$$Q_{\lim_{1D}} \approx \left(7.46 \times 10^{-3}\, w\right) \left[\frac{0.7 cm}{\left(\frac{2\pi R}{rev}\right)\left(\frac{4 rev}{\sec}\right)} \right]$$

$$Q_{\lim_{1D}} \approx \left(7.46 \times 10^{-3}\ J/\sec\right) \left[\frac{0.7 cm - \sec}{8\pi \cdot R} \right]$$

$$Q_{\lim_{1D}} \approx \left[\frac{207.8 \times 10^{-6}\, J - cm}{R} \right] \qquad \text{For: } R \leq 882\ \ cm$$

A plot, of the radiant energy transmitted through the limiting aperture, per revolution of the rotating mirror, as a function of the radial distance from the rotating mirror (for radial distances less than, or equal to 882 centimeters) presented in figure 11 on page 23.

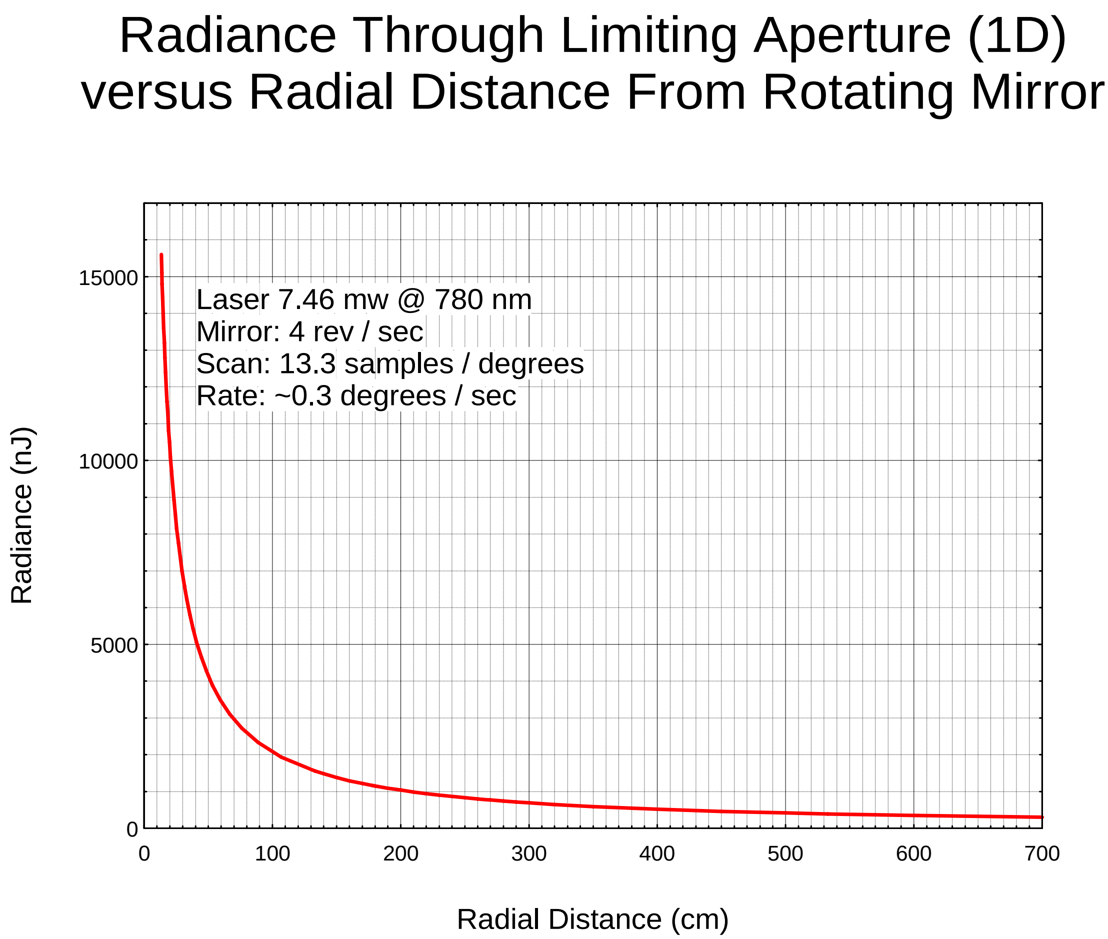


Figure 11

The plot depicts the one-dimensional approximation of the radiant energy transmitted through the limiting aperture as a function of the radial distance, for distances less than 882 centimeters. The radiant power of the scanning laser beam was corrected for the transmission losses at the exit window. The (1D) estimated transmitted radiance has a conservative safety bias.

2. **Two Dimensional Method (ratio of areas)**

The two-dimensional (2D) method of determining the radiant energy transmitted through the limiting aperture as a function of the incident **laser power** (Φ), **mirror rotation rate** (ω) and can be expressed as a function of the **radial distance** (R).

Where the scan width over fills the limiting aperture.

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega}\right)\left[\frac{A_{\lim}}{(2\pi \cdot R)\cdot w}\right] \quad J \qquad\qquad \text{For: } w \le d_{\lim}$$

Where;

$Q_{\lim_{2D}}$:	Radiant energy (2D method) transmitted through the limiting aperture (joules).
$A_{\lim}$:	Area of the limiting aperture (cm^2).

The radial distance, where the laser beam width (w) is equal to the limiting aperture ($d_{\lim}$) was shown to be 882 centimeters (page 21).

Determination of radiant energy transmitted through the limiting aperture

General assumptions

1. The cross sectional area of the scanned laser beam is assumed to be circular.

$$A_{beam} = \frac{\pi}{4}(D)^2$$

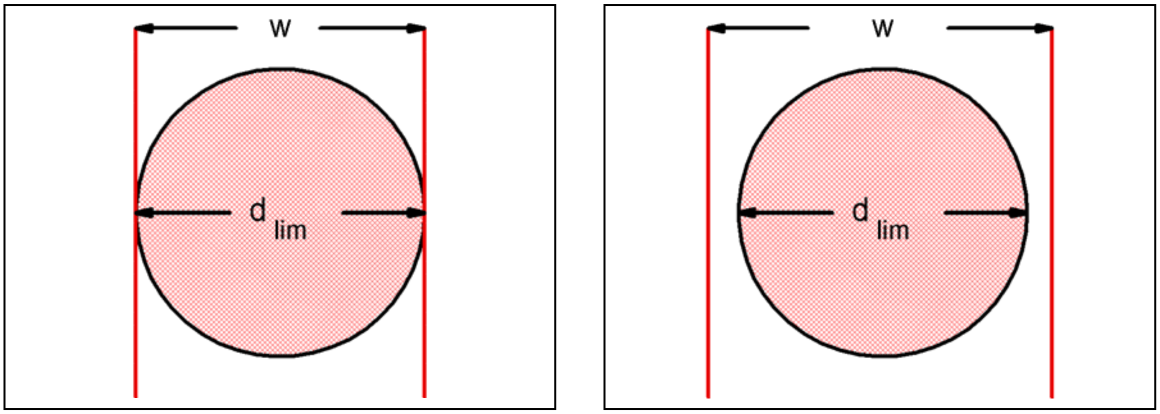
2. The power distribution across the beam is assumed to be uniform, spatially as well as temporally.

$$H_{beam} = \frac{\Phi}{A_{beam}}$$

3. The irradiance of the scanned area is assumed to be uniform, spatially as well as temporally.

$$H_{scan} = \frac{\Phi}{A_{scan}}$$

At the radial distance where: $R \geq R_{w=d_{\lim}}$



$w = d_{\lim}$ $\qquad\qquad$ $w > d_{\lim}$

<u>Figure 12</u>

The radiant energy transmitted through the limiting aperture at radial distances from the rotating mirror, where the laser beam width is equal or greater than the diameter of the limiting aperture.

The radiant energy transmitted through the limiting aperture at radial distances (from the rotating mirror) where the laser beam width is equal to or greater than the limiting aperture, presented in *ANSI Std. Z136.1-2000 (Table 8*), is directly proportional to the ratio of areas (page 14).

$$Q_s = \left(\frac{\Phi}{\omega}\right) \cdot \left[\frac{A_\tau}{A_{scan}}\right]$$

(Refer to page 14)

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega}\right) \cdot \left[\frac{A_{\lim}}{A_{scan}}\right]$$

Where;

$Q_{\lim_{2D}}$:	Radiant energy transmitted through the limiting aperture (joules).
Φ :	Laser beam radiant power (watts).
ω :	Mirror rotation rate (revolutions/second).
$A_{\lim}$:	Area of the limiting aperture (cm^2).
A_{scan} :	Beam area of a single-scan (cm^2).

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega}\right) \cdot \left[\frac{\frac{\pi}{4}(d_{\lim})^2}{w \cdot 2\pi R}\right]$$

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega}\right) \cdot \left[\frac{(d_{\lim})^2}{8 \cdot w \cdot R}\right] \qquad \text{Where: } R \geq R_{w=d_{\lim}}$$

Recall from page 21 that the radial distance where the beam width is equaled to the limiting aperture is 882 centimeters.

The radiant energy transmitted through the limiting aperture can be expressed as a function of the radial distance from the rotating mirror.

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega}\right) \cdot \left[\frac{(d_{\lim})^2}{(8) \cdot \{d_o + \theta(r+R)\} \cdot R}\right] \qquad \text{Where: } R \geq 882 \;\; cm$$

Where;

$Q_{\lim}$:	Radiant energy transmitted through the limiting aperture (joules).
Φ :	Laser beam radiant power (watts).
ω :	Mirror rotation rate (revolutions/second).
$d_{\lim}$:	Diameter (cm) of the limiting aperture [*ANSI Std.Z136.1-2000 (Table 8)*].
d_o :	Exit diameter of the beam at the laser (cm).
θ :	Beam divergence (radians).
r :	Distance from the laser to the rotating mirror (cm).
R :	Radial distance from the rotating mirror (cm).

Determination of, $Q_{\lim 2D}$ @ $R = 882\ cm$**:**

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega}\right) \cdot \left[\frac{(d_{\lim})^2}{(8) \cdot \{d_o + \theta(r + R)\} \cdot R}\right]$$

Incident Radiant Power

The incident radiant power at the limiting aperture is:

$$\Phi = 7.46\ mw \qquad \text{(Refer to page 21)}$$

Evaluation of $Q_{\lim_{2D}}$ @ $R = 882\ cm$

$$Q_{\lim_{2D}} = \left(\frac{7.46 \times 10^{-3}\, watts}{4\, {}^{rev}\!/_{\sec}}\right) \times \left[\frac{(0.7\ cm)^2\, rev}{(8) \cdot \left\{\ 0.25\ cm + \left(0.5 \times 10^{-3}\right) (18\ cm + 882\ cm)\right\} \cdot (882\ cm)}\right]$$

$$Q_{\lim_{2D}} = 185 \times 10^{-9}\, J$$

Number of Scan Increments Across the Limiting Aperture as a Function of the Radial Distance

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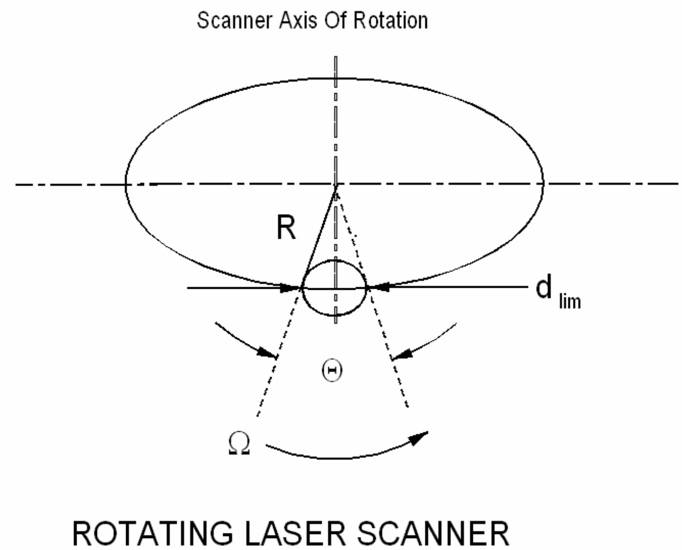


Figure 13

Laser Scanner sweeps across the limiting aperture.

The number of pulses transmitted through the limiting aperture as the scanner sweeps across the limiting aperture can be shown to also be a function of the radial distance (R) from the rotating mirror.

Scan Increment Across the Limiting Aperture

Let n be the number of complete scans transmitted through the limiting aperture.

$$\Theta_n = n \cdot \Theta$$

Where;

Θ_n :	Angular sweep for "n" number of mirror scans.
n :	Number of mirror scans (sweep increments).
Θ :	Single incremental angular sweep between two-mirror scans.

$$\Theta = 1.31 \times 10^{-3} radians$$ (Refer to page 18)

$$\Theta_n = n \cdot \left(1.31 \times 10^{-3} radians\right)$$

The radial distance from the rotating mirror for "n" incremental scans swept through the limiting aperture then can be expressed as function of the "n" number of single increment angles.

$$R_n = \frac{d_{\lim}}{\Theta_n}$$

$$R_n = \frac{0.7\ cm}{n \cdot \left(1.31 \times 10^{-3} radians\right)}$$

$$R_n = \frac{533.4\ cm}{n}$$

Table 1

Radial Distances For The First Ten Incremental Mirror Scans Through The Limiting Aperture

Mirror Scans (n)	Θ_n (radians)	R_n (cm)
1	1.31×10^{-3}	533.4
2	2.62×10^{-3}	266.7
3	3.93×10^{-3}	177.8
4	5.24×10^{-3}	133.4
5	6.55×10^{-3}	106.7
6	7.87×10^{-3}	88.9
7	9.18×10^{-3}	76.2
8	10.5×10^{-3}	66.7
9	11.8×10^{-3}	59.3
10	13.1×10^{-3}	53.3

The time it takes for the Laser Scanner to sweep across the limiting aperture, the **limiting aperture sweep time** ($T_{\lim}$) is related to the sweep rate (Ω) and the radial distance (R) from the rotating mirror.

$$T_{\lim} = f(R_n) = \frac{\Theta_n}{\Omega}$$

For the default configuration of the DeltaSphere-3000:

$$\Omega = 5.25 \times 10^{-3} \ \ radians / \sec$$

$$T_{\lim_n} = n \cdot \frac{1.312 \ \ radians}{5.25 \times 10^{-3} \ radians \big/ \sec} = n(0.25 \sec)$$

Table 2 depicts the time needed for the first ten incremental sweeps across the limiting aperture.

Table 2

Limiting Aperture Sweep Time

Mirror Scans n	R_n (cm)	$T_{\lim}$ (sec)
1	533.4	0.25
2	266.7	0.50
3	177.8	0.75
4	133.4	1.00
5	106.7	1.25
6	88.9	1.50
7	76.2	1.75
8	66.7	2.00
9	59.3	2.25
10	53.3	2.50

Transmitted Radiant Energy (2D)

Refer to Appendix 1 through 4 for the specific determination of the radiant energy transmitted through the limiting aperture at specific radial distances using the 2D method.

In general, the radiant energy (2D) transmitted through the limiting aperture per scan is of the form:

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega}\right)\cdot\left[\frac{A_\tau}{A_{scan}}\right]$$

(Refer to page 25)

Where;

$Q_{\lim_{2D}}$:	Radiant energy (2D) transmitted through the limiting aperture (joules).
Φ :	Laser beam radiant power (watts).
ω :	Mirror rotation rate (revolutions/second).
A_τ :	Beam area transmitted through the limiting aperture (cm^2).
A_{scan} :	Beam area of a single-scan (cm^2).

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega}\right)\cdot\left[\frac{A_\tau}{w\cdot(2\pi R)}\right]$$

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega}\right)\cdot\left[\frac{A_\tau}{(d_o+\theta(r+R))\cdot(2\pi\cdot R)}\right]$$

For the radial distances where the range (R) is: $R_1 \le R < R_{w=d_{\lim}}$

The beam area transmitted through the limiting aperture for a **single mirror scan** at the radial distance range ($R_1 \le R < R_{w=d_{\lim}}$) was shown (Appendix 1) to be as follows:

In the radial distance range: $533.4\ cm \le R < 882\ cm$, the transmitted beam area is as follows.

$$A_\tau = A_{\lim}\left(\frac{\sin^{-1}\left(\frac{\{d_o + \theta(r+R)\}}{d_{\lim}}\right)}{90^\circ}\right) - \frac{d_{\lim}\cdot\{d_o + \theta(r+R)\}}{2}\cdot\cos\left(\sin^{-1}\left(\frac{\{d_o + \theta(r+R)\}}{d_{\lim}}\right)\right)$$
$$+ d_{\lim}\cdot\{d_o + \theta(r+R)\}\cdot\cos\left(\sin^{-1}\left(\frac{\{d_o + \theta(r+R)\}}{d_{\lim}}\right)\right)$$

The scan area at the radial distance: R=533.4 cm:

$$A_{scan} = 2\pi R\cdot w$$

$$w = 0.526\ cm$$

$$A_{scan} = 2\pi(533.4\ cm)\cdot(0.526\ cm)$$

$$A_{scan} = 1762\ cm^2$$

[Single Transmitted Scan Area] At the radial distance: R = 533.4 cm

The transmitted radiance (for the 2D method) is:

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega}\right)\cdot\left[\frac{A_\tau}{A_{scan}}\right]$$ (Refer to page 25)

$$Q_{\lim_{2D(R=533.4cm)}} = \left(\frac{7.46\times10^{-3}\,watts}{4\,{}^{rev}\!/\!_{\sec}}\right)\cdot\left(\frac{0.33\ cm^2 - rev}{1762\ cm^2}\right)$$

The average “pulsed” radiant energy (2D determination) transmitted through the limiting aperture at the radial distance of approximately 533 centimeters is 349 nanojoules.

$$Q_{\lim_{2D(R=533.4cm)}} = 349\times10^{-9}\ J$$

At the radial distance: R = 700 cm (Intermediate Radial Distance)

$$Q_{\lim_{2D(R=700cm)}} = \left(\frac{7.46 \times 10^{-3} watts}{4 \, {}^{rev}\!/\!_{\sec}} \right) \cdot \left(\frac{0.36 \;\; cm^2 - rev}{2679 \;\; cm^2} \right)$$

$$Q_{\lim_{2D(R=700cm)}} = 253 \times 10^{-9} \;\; J$$

[Two-Scan Transmission] At the radial distance: R = 266.7 cm

The transmitted radiance (for the 2D method):

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega} \right) \cdot \left[\frac{A_\tau}{A_{scan}} \right]$$ (Refer to page 25)

See Appendix 2 for specific derivation for a two-scan transmission through the limiting aperture and determination of the scan area.

$$Q_{\lim_{2D(R=266.7cm)}} = \left(\frac{7.46 \times 10^{-3} watts}{4 \, {}^{rev}\!/\!_{\sec}} \right) \cdot \left(\frac{0.222 \;\; cm^2 - rev}{657 \;\; cm^2} \right)$$

The average "pulsed" radiant energy (2D) transmitted through the limiting aperture at a radial distance of 266.7 centimeters is: 630 nanojoules.

$$Q_{\lim_{2D(R=266.7cm)}} = 630 \times 10^{-9} \;\; J$$

[**Three-Scan Transmission]** At the radial distance where: R = 177.8 cm

$$Q_{\lim_{2D}} = \left(\frac{\Phi}{\omega}\right) \cdot \left[\frac{A_{\tau}}{A_{scan}}\right]$$ (Refer to page 25)

See Appendix 3 for specific derivation for a three-scan transmission through the limiting aperture and the determination of the scan area.

$$Q_{\lim_{2D(R=177.8cm)}} = \left(\frac{7.46\times10^{-3}\,watts}{4\,rev/\sec}\right) \cdot \left(\frac{0.229\ \ cm^2 - rev}{388.7\ \ cm^2}\right)$$

The average "pulsed" radiant energy (2D) transmitted through the limiting aperture at a radial distance of 177.8 centimeters is: 1.10 microjoules

$$Q_{\lim_{2D(R=177.8cm)}} = 1.10\times10^{-6}\ \ J$$

[**Four-Scan Transmission**] At the radial distance where: R = 133.4 cm

See Appendix 4 for specific derivation for a four-scan transmission through the limiting aperture.

$$Q_{\lim_{2D}} = \frac{\Phi}{\omega} \cdot \frac{A_{\tau}}{A_{scan}}$$ (Refer to page 25)

$$Q_{\lim_{2D(R=133.4cm)}} = \left(\frac{7.46\times10^{-3}\,watts}{4\,rev/\sec}\right) \cdot \left(\frac{0.219\ \ cm^2 - rev}{272.9\ \ cm^2}\right)$$

The average "pulsed" radiant energy transmitted through the limiting aperture at a radial distance of 133.4 centimeters is: 1.5 microjoules

$$Q_{\lim_{2D(R=133.4cm)}} = 1.5\times10^{-6}\ \ J$$

Table 3

Radiant Energy Transmitted (2D) Through the "Limiting Aperture" At Specific Radial Distances

n	R_n (cm)	Q_{lim} * (J)
-	882.0	185×10^{-9}
-	700.0	253×10^{-9}
1	533.4	349×10^{-9}
2	266.7	630×10^{-9}
3	177.8	1.10×10^{-6}
4	133.4	1.50×10^{-6}

Values calculated by Excel Spreadsheet Model of the 3rd Tech Scanner
*The value of the transmitted radiant energy was determined from the 2D method.

Refer to appendix 1 through appendix 4 and appendix 6 for the determination and calculation of the values presented in Table 3.

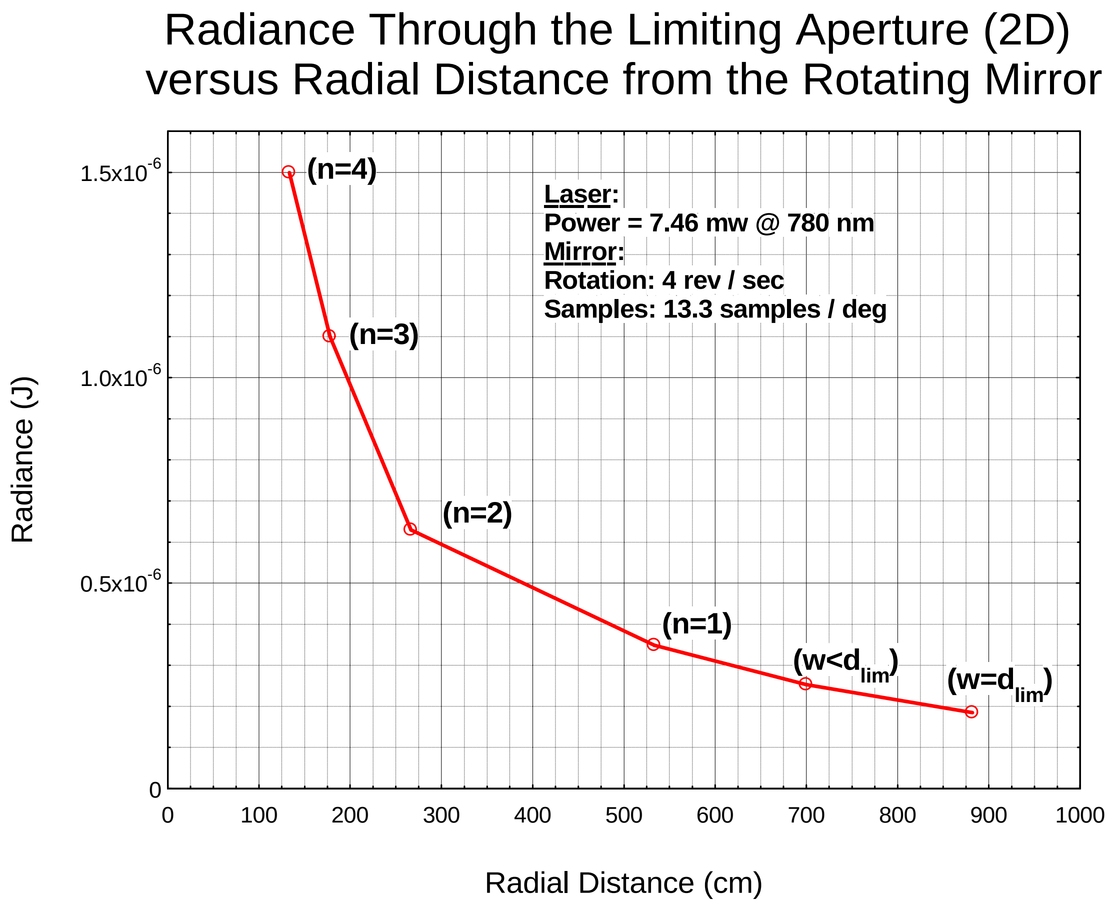


Figure 14

A plot to the radiant energy (2D method) transmitted through the limiting aperture at radial distances specific to certain pulse event numbers.

Figure 14 depicts the plot of the average "pulsed" radiant energy, as determined by the 2D method, transmitted through the limiting aperture, per revolution of the rotating mirror, at the radial distances (less than or equal to 882 centimeters) specific to 1, 2, 3, and 4 pulse events (vertical scans) per (horizontal) sweep across the limiting aperture as well as other radial distances of concern.

C. **Pulse Exposure Time**

The pulse duration is a function of the transmitting aperture and the radial distance (refer to page 13). Where the transmitting aperture is set to the limiting aperture:

$$t = \frac{d_{\lim}}{2\pi R \cdot \omega} \quad \text{sec}$$

$$t = \frac{0.7cm}{\left(\frac{2\pi \cdot R}{rev}\right)\left(\frac{4\ rev}{\text{sec}}\right)}$$

The pulse width for the default configuration of the DeltaSphere-3000 as a function of the radial distance can be expressed as follows.

$$t = \frac{27.85 \times 10^{-3} cm - \text{sec}}{R}$$

For radial distances less than or equaled to 882 centimeters the **shortest** pulse-exposure time is calculated at the radial distance of 882 centimeters.

$$t = \frac{0.7cm}{\left(\frac{2\pi \cdot 882cm}{rev}\right)\left(\frac{4\ rev}{\text{sec}}\right)}$$

$$t = 31.58 \times 10^{-6}\ \text{sec}$$

D. **Maximum Permissible Exposure**

The **maximum permissible exposure** (*MPE*) for a multiple pulse exposure is always the smallest of the MPE values derived through the evaluation of ANSI Rule 1 through ANSI Rule 3 [*ANSI Std. Z136.1-2000 (8.2.3.2)*].

$$MPE = \min \left[MPE_{rule1},\ MPE_{rule2},\ MPE_{rule3} \right]$$

Rule 1 (Single Pulse)

The single pulse MPE is given in *Table 5a* of the *ANSI Std. Z136.1-2000* for various exposure times. Since the shortest exposure time was shown to be approximately 31 microseconds (page 37) the following MPE form is the appropriate formula to use in the determination of the Rule 1 MPE.

$$MPE_{Rule1} = 1.8\ C_A\ t^{0.75} \times 10^{-3}\quad {}^{J}\!/_{cm^2} \qquad 700nm < \lambda < 1050nm$$

$$18 \times 10^{-6}\ \sec < t < 10 \sec$$

The **wavelength correction coefficient** (C_A) is given in *Table 6* of the *ANSI Std. Z136.1-2000* as:

$$C_A = 10^{2(\lambda - 0.7)}$$

$$C_A = 10^{2(0.76 - 0.7)}$$

$$C_A = 1.445$$

$$MPE_{rule1} = (1.8)\ (1.445)\ t^{0.75} \times 10^{-3}\quad {}^{J}\!/_{cm^2}$$

$$MPE_{rule1} = (2.602)\ t^{0.75} \times 10^{-3}\quad {}^{J}\!/_{cm^2}$$

The exposure time (t) is a function of the radial distance from the rotating mirror (refer to page 37).

$$MPE_{rule1} = (2.602)\left[\frac{27.85\times10^{-3}}{R}\right]^{0.75}\times10^{-3} \quad {}^{J}\!/_{cm^2}$$

ANSI Rule 1 MPE as a function of the radial separation distance can be expressed:

$$MPE_{rule1} = \frac{177.4\times10^{-6}}{R^{0.75}} \quad {}^{J}\!/_{cm^2}$$

Rule 2 (Average Power MPE)

The **pulse repetition rate** (*PRF*) is related to the mirror rotation rate, since there is one pulse event at the limiting aperture for each revolution of the rotating mirror, as it sweeps across the limiting aperture.

$$PRF = \omega = 4\ {}^{rev}\!/_{\sec}$$

$$PRF = 4 \ \sec^{-1}$$

The **critical frequency** (f_c) for multiple pulse exposures of wavelengths from 400 nm to 1050 nm is 55 KHz [*ANSI Std. Z136.1-2000 (8.2.3.2-note)*]. Since the PRF is less than the critical frequency for this wavelength band ANSI Rule 2 would not apply and need not be evaluated.

$$PRF < f_c = 55\times10^{3} \ \sec^{-1}$$

Rule 3 (Multiple Pulse)

The ANSI Rule 3 MPE is the produce of the ANSI Rule 1 MPE and a **multiple pulse correction factor** (C_p).

$$MPE_{Rule3} = C_p \cdot MPE_{rule1}$$

The **multiple-pulse correction factor** (C_p) is given in *Table 6* of the *ANSI Std. Z136.1-2000*.

$$C_p = n^{-0.25}$$

Where "n" is the number of pulses in the exposure (T).

$$n = PRF \cdot T$$

The number of pulse events in the exposure (T) is.

$$n = \omega \cdot T$$

The time it takes for the Laser Scanner to sweep across the limiting aperture, the **limiting aperture sweep time** ($T_{\lim}$) is related to the sweep rate (Ω) and the radial distance (R) from the rotating mirror.

$$T_{\lim} = f(R) = \frac{\Theta}{\Omega}$$

$$T_{\lim} = \frac{d_{\lim}}{\Omega \cdot R}$$

$$T_{\lim} = \frac{0.7cm}{\left(5.25\times10^{-3}\sec^{-1}\right) \quad R}$$

The **limiting aperture sweep time** ($T_{\lim}$) is then expressed as:

$$T_{\lim} = \frac{133.4 \ cm - \sec}{R}$$

There is one pulse event transmitted through the limiting aperture for each mirror- rotation (scan) as it sweeps across the limiting aperture horizontally.

The time between each pulse, the **pulse period**, (T) is related to the mirror rotation rate (ω).

For the default configuration of the DeltaSphere-3000

$$T = \frac{1}{\omega} = \frac{1 \ rev}{4 \ rev/\sec}$$

$$T = 0.25 \ \sec$$

The **integer pulse exposure time** (T_n) is the product of the number of pulses transmitted through the limiting aperture and the pulse period between the pulses.

$$T_n = n \cdot T$$

$$T_n = n \ (0.25 \ \sec)$$

The number of pulses used in the evaluation of the ANSI Rule 3 MPE is dependent on the radial distance of the limiting aperture from the rotating mirror and the sweep time across the limiting aperture.

The radial distance associated with this limiting aperture sweep time is then:

$$R = \frac{133.4 \ cm - \sec}{T_{\lim}}$$

The radial distance (R_n) for the integer number of pulses transmitted through the limiting aperture can be related to the integer pulse exposure time.

$$R_n = \frac{133.4 \ cm - \sec}{T_n}$$

$$R_n = \frac{133.4 \ cm - \sec}{n \ \ (0.25 \ \sec)}$$

The radial distance for the integer number of pulses transmitted through the limiting aperture can be expressed as a function of the integer number pulses in the exposure.

$$R_n = \frac{533.4 \ cm}{n}$$

Where, (R_n) is the longest radial distance from the rotating mirror where the number of pulses transmitted through the limiting aperture is just equal to “n”. A unique radial distance for each “n” gives rise to a unique pulse exposure (t) with a unique ANSI Rule 1 MPE and a unique ANSI rule 3 MPE as a function of the number of pulses.

The MPE(s) for ANSI Rule 1 and Rule 3 should be evaluated for each “n”. A sample of several various pulse counts are presented in Table 4 on page 45.

E. **The Allowable Emission Limit**

The laser class Allowable Emission Limit (AEL) is the highest emission a laser may have and still be considered to be a member of a particular laser hazard class. From the perspective of an observer the AEL may also be considered an Allowable Exposure Limit. The Laser Hazard Class 1 AEL is defined as the product of the appropriate MPE and the area associated with the limiting aperture [*ANSI Std. Z136.1-2000 (3.2.3.4.1-(2))*] and is simply referred to as "AEL".

$$AEL \equiv MPE \times A_{\lim}$$

$$AEL = MPE \times \frac{\pi}{4}(0.7cm)^2$$

$$AEL = \left(0.385 \ \ cm^2\right) \ \cdot MPE$$

Example Evaluation for a two pulse event ($n = 2$):

The radial distance for a two-pulse event is:

$$R_2 = \frac{533.4 \ \ cm}{2}$$

$$R_2 = 266.7 \ \ cm$$

The pulse exposure time is:

$$t = \frac{27.85 \times 10^{-3} \ \ cm - \sec}{266.7 \ \ cm}$$

$$t = 104.4 \times 10^{-6} \sec$$

The ANSI Rule 1 MPE is:

$$MPE_{rule1} = \frac{177.4 \times 10^{-6} \ J/cm^2}{(266.7)^{0.75}}$$

$$MPE_{rule1} = 2.688 \times 10^{-6} \ J/cm^2$$

The ANSI Rule 3 MPE is

$$MPE_{rule3} = (2)^{-0.25} \left[2.688 \times 10^{-6} \ J \big/ cm^2\right]$$

$$MPE_{rule3} = (0.841) \left(2.688 \times 10^{-6}\right) \ J \big/ cm^2$$

$$MPE_{rule3} = 2.260 \times 10^{-6} \ J \big/ cm^2$$

The appropriate MPE is the MPE derived from ANSI Rule 3 and the area of the limiting aperture had been previously determined (page 43).

The appropriate $AEL_{n=2}$ for a two pulse event is:

$$AEL_{n=2} = \left(0.385 \ cm^2\right) \left(2.260 \times 10^{-6} \ J \big/ cm^2\right)$$

$$AEL_{n=2} = 870.1 \times 10^{-9} \ J$$

The average "pulsed" radiance (2D) transmitted through the limiting aperture for a two pulse event had previously been determined and tabulated in Table 3 on page 35 to be:

$$Q_{\lim} = 630 \times 10^{-9} \ J$$

The associated MPE for each integer "n" in a sampling of various n(s) were evaluated, the appropriate AEL was determined and compared to the radiance (1D) transmitted through the limiting aperture and is presented in the Table 4 on page 45 and compared to the transmitted radiance (2D) presented in Table 5.

<u>Table 4</u>

Summary of MPE(s), AEL(s) and Transmitted Radiant Energies (1D)

n	R (cm)	t (μsec)	MPE_{rule1} (μJ/cm^2)	C_p	MPE_{rule3} (μJ/cm^2)	AEL (nJ)	Q_{lim}* (nJ)
1	533.4	52.22	1.598	1.000	1.597	615.4	417.8
2	266.7	104.4	2.686	0.841	2.259	870.1	835.5
3	177.8	156.7	3.651	0.760	2.767	1,065	1,255
4	133.3	208.9	4.518	0.707	3.194	1,230	1,674
5	106.7	261.1	5.344	0.669	3.574	1378	2089
6	88.90	313.3	6.127	0.639	3.917	1507	2506

*Calculated by the one-dimensional method.

<u>Table 5</u>

Summary of MPE(s), AEL(s) and Transmitted Radiant Energies (2D)

n	R (cm)	t (μsec)	MPE_{rule1} (μJ/cm^2)	C_p	MPE_{rule3} (μJ/cm^2)	AEL (nJ)	Q_{lim}* (nJ)
1	533.4	52.22	1.598	1.000	1.597	615.4	348.9
2	266.7	104.4	2.686	0.841	2.259	870.1	629.7
3	177.8	156.7	3.651	0.760	2.767	1,065	1,100
4	133.3	208.9	4.518	0.707	3.194	1,230	1,499

*Calculated by the two-dimensional method.

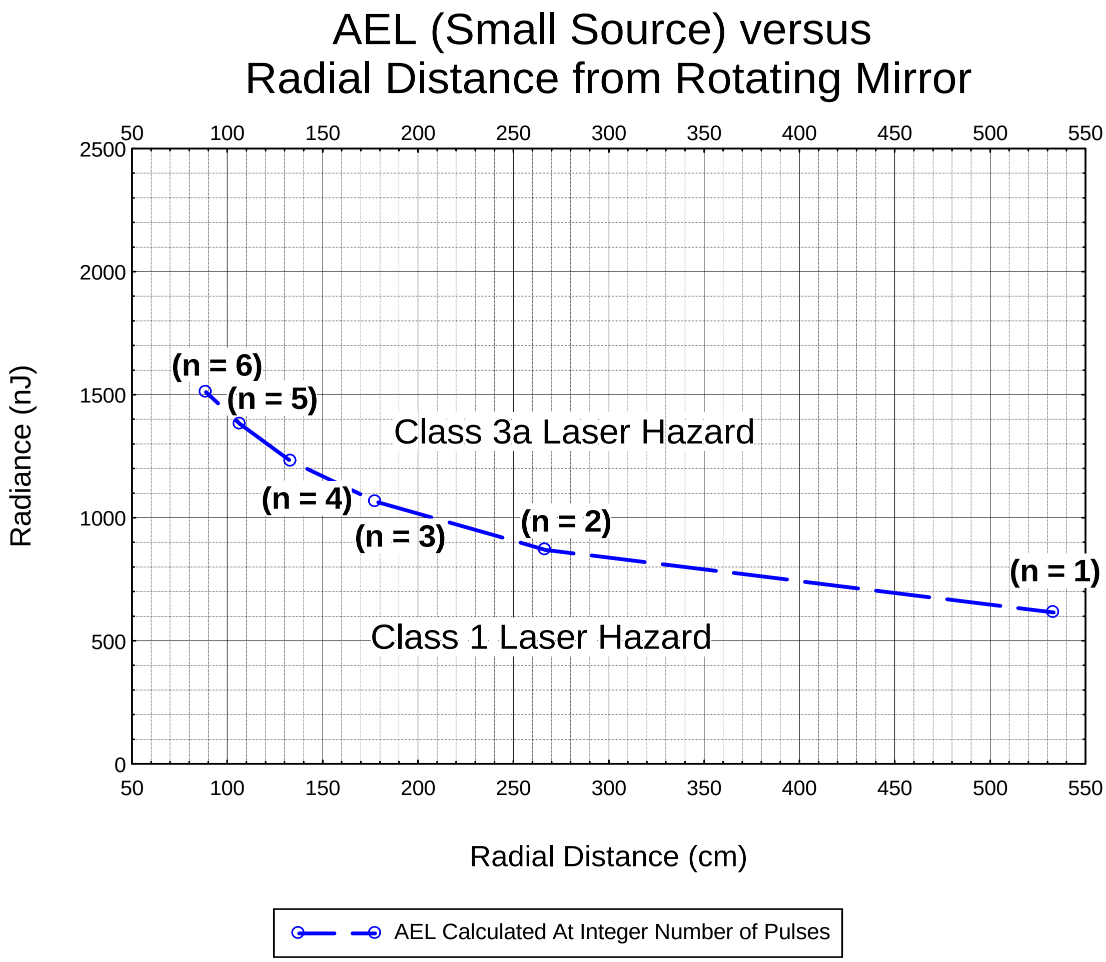


Figure 15

Figure 15 presents the plot of the AEL versus the radial distance from the rotating mirror.

Class 3a versus Class 1 Laser Hazards

Radiant energy levels just above the AEL present a Class 3a Laser Hazard whereas those below the AEL are a Class 1 Laser Hazard and are considered "eye safe".

F. Ocular Hazard versus Eye Safe

1. Eye Safe Zone

The radiance transmitted through the limiting aperture is less than the Class 1 AEL throughout the "eye safe" zone.

$$Q_{\lim_{eye\ safe}} < AEL$$

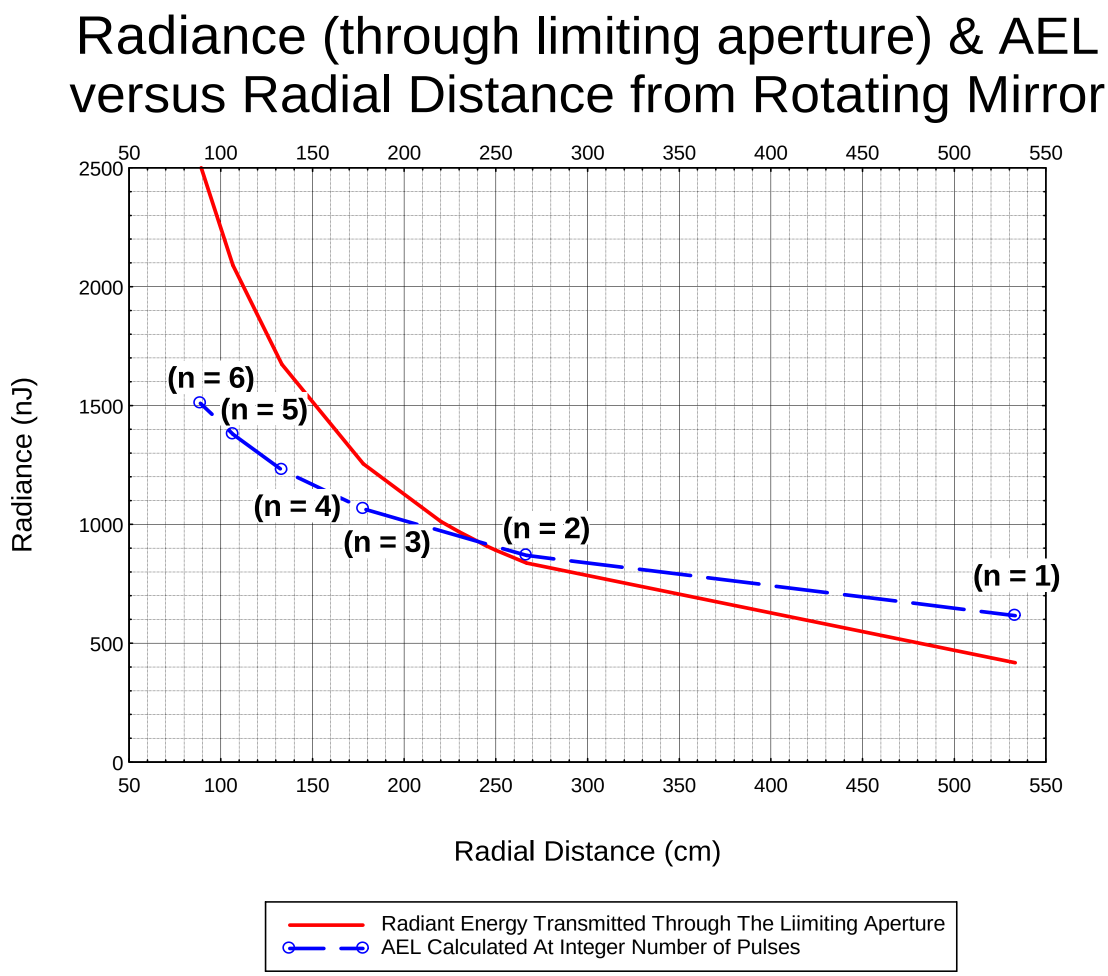


Figure 16

The plot of the radiant energy (one-dimensional method) transmitted through the limiting aperture and the appropriate AEL at various radial distances from the rotating mirror yields a small source Nominal Ocular Hazard Distance of approximately 245 centimeters.

2. Ocular Hazard Zone

The radiance transmitted through the limiting aperture is greater than the Class 1 AEL throughout the ocular hazard zone.

$$Q_{\lim} > AEL$$

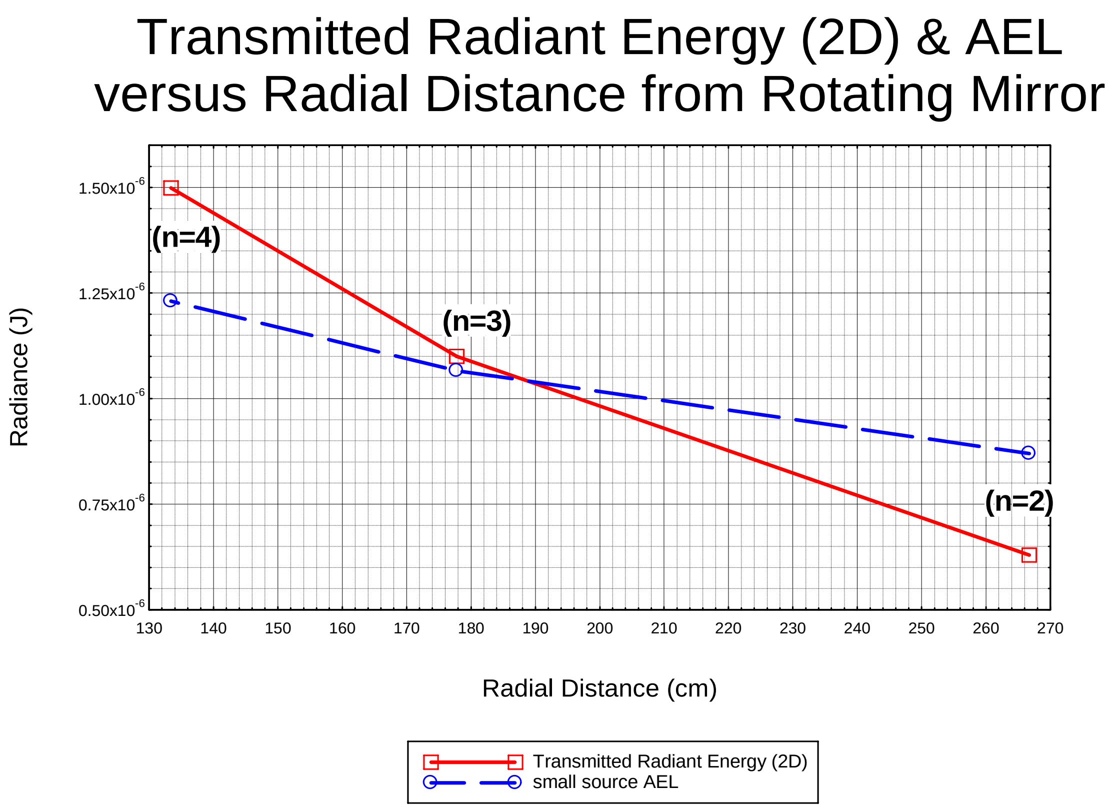


Figure 17

The plot of the radiant energy (two-dimensional method) transmitted through the limiting aperture and the appropriate AEL at various radial distances from the rotating mirror yields a small source Nominal Ocular Hazard Distance of approximately 188 centimeters.

3. Nominal Ocular Hazard Distance

The **Nominal Ocular Hazard Distance** (NOHD) is that distance at which the radiance through the limiting aperture is equal to the Class 1 AEL and direct intrabeam viewing of the laser is considered eye-safe.

$$Q_{\lim} = AEL$$

The NOHD (from the rotating mirror) is that radial distance (R_{NOHD}) where the radiant energy transmitted through the limiting aperture is equal to the Class 1 AEL.

4. NOHD (1D Method-Graphic Determination)

With reference to the plot (figure 16) derived from Table 4 (page 45) using the one-dimensional method for determining the radiant energy transmitted through the limiting aperture the NOHD lies somewhere between pulse-count "n = 2" and "n = 3" and is on the order of ~245 cm (with a conservative safety bias).

$$R_{n=3} < NOHD < R_{n=2}$$

$$177.8\ cm < NOHD < 266.7\ cm$$

5. NOHD (2D Method-Graphic Determination)

With reference to the plot (figure 17) derived from Table 5 (page 45) employing the more accurate two-dimensional method of determining the radiant energy transmitted through the limiting aperture the small source NOHD also lies somewhere between pulse-count "n = 2" and "n = 3" and is on the order of ~188 cm.

$$R_{n=3} < NOHD < R_{n=2}$$

$$177.8\ cm < NOHD < 266.7\ cm$$

6. NOHD (1D-Analytical Determination)

The radiant energy transmitted through the limiting aperture ($Q_{\lim}$) as well as the AEL are functions of the radial distance (R) from the rotating mirror. The NOHD occurs at the radial distance where there is equality between transmitted radiant energy and the AEL.

$$Q_{\lim_{1D}} = AEL$$

It was shown that for the 1D approach the transmitted radiance is a function of the radial distance (page 16);

$$Q_{\lim_{1D}} = f(R)$$

$$Q_{\lim_{1D}} = \left(\frac{\Phi}{\omega}\right)\cdot\left(\frac{d_{\lim}}{2\pi R}\right) = \frac{\Phi\cdot d_{\lim}}{2\pi R\cdot\omega} = \left(\frac{\Phi\cdot d_{\lim}}{2\pi\omega}\right)\cdot\frac{1}{R}$$

The Class 1 AEL can be expressed as follows.

$$AEL = A_{\lim}\cdot MPE_{rule3}$$

$$AEL = \left(1.8\times10^{-3}\right)A_{\lim}\cdot C_A\cdot C_p\cdot t^{0.75}$$

The multiple pulse correction [*ANSI Std. Z136-2000 (Table 6)*] is:

$$C_p = n^{-0.25} = \left(PRF\cdot T\right)^{-0.25} = \left(\omega\cdot T\right)^{-0.25}$$

The transit time to sweep through the limiting aperture (page 40) was shown to be a function of the radial distance.

$$T = f(R)$$

$$T = \frac{d_{\lim}}{\Omega R} = \left(\frac{d_{\lim}}{\Omega}\right)\cdot\frac{1}{R}$$

$$\Omega = \Theta\cdot\omega \qquad \text{(Refer to page 19)}$$

$$T = \left(\frac{d_{\lim}}{\Theta\cdot\omega}\right)\cdot\frac{1}{R}$$

$$\Theta = \left(\frac{\deg}{N}\right)\cdot\left(\frac{\pi\ \ radians}{180^{\circ}}\right) \qquad \text{(Refer to page 18)}$$

The transit time to sweep across the limiting aperture as a function of the radial distance can be expressed as follows.

$$T_{\lim} = \left[\frac{180 \cdot d_{\lim} \cdot N}{\omega \cdot \pi}\right] \cdot \left(\frac{1}{R}\right)$$

The multiple pulse correction as a function of the radial distance is as follows.

$$C_p = \left(\omega \cdot \left[\frac{180 \cdot d_{\lim} \cdot N}{\omega \cdot \pi}\right] \cdot \left(\frac{1}{R}\right)\right)^{-.0.25} = \left(\left[\frac{180 \cdot d_{\lim} \cdot N}{\pi}\right] \cdot \left(\frac{1}{R}\right)\right)^{-.0.25}$$

$$C_p = \left[\frac{180 \cdot d_{\lim} \cdot N}{\pi}\right]^{-0.25} \cdot \left(\frac{1}{R}\right)^{-0.25}$$

The radiant exposure time was shown to be a function of the aperture size and the radial distance from the rotating mirror (page 13).

$$t = \left(\frac{d_{\lim}}{2\pi \cdot \omega}\right) \cdot \left(\frac{1}{R}\right)$$

The NOHD can be determined by applying the various functions of the radial distance to the equality presented on page 47:

$$Q_{\lim_{1D}} = AEL$$

$$\left(\frac{\Phi \cdot d_{\lim}}{2\pi\omega}\right) \cdot \frac{1}{R} = \left(1.8 \times 10^{-3}\right) A_{\lim} \cdot C_A \cdot \left[\frac{180 \cdot d_{\lim} \cdot N}{\pi}\right]^{-0.25} \cdot \left(\frac{1}{R}\right)^{-0.25} \cdot \left[\left(\frac{d_{\lim}}{2\pi \cdot \omega}\right) \cdot \left(\frac{1}{R}\right)\right]^{0.75}$$

$$\left(\frac{\Phi \cdot d_{\lim}}{2\pi\omega}\right) \cdot \frac{1}{R} = \left(1.8 \times 10^{-3}\right) A_{\lim} \cdot C_A \cdot \left[\frac{180 \cdot d_{\lim} \cdot N}{\pi}\right]^{-0.25} \cdot \left(\frac{1}{R}\right)^{-0.25} \cdot \left[\left(\frac{d_{\lim}}{2\pi \cdot \omega}\right)\right]^{0.75} \cdot \left(\frac{1}{R}\right)^{0.75}$$

$$\left(\frac{\Phi \cdot d_{\lim}}{2\pi\omega}\right) \cdot \frac{1}{R} = \left\{\left(1.8 \times 10^{-3}\right) A_{\lim} \cdot C_A \cdot \left[\frac{180 \cdot d_{\lim} \cdot N}{\pi}\right]^{-0.25} \cdot \left[\left(\frac{d_{\lim}}{2\pi \cdot \omega}\right)\right]^{0.75}\right\} \cdot \left(\frac{1}{R}\right)^{-0.25} \cdot \left(\frac{1}{R}\right)^{0.75}$$

$$\frac{\left(\frac{\Phi \cdot d_{\lim}}{2\pi\omega}\right)}{\left\{\left(1.8 \times 10^{-3}\right) A_{\lim} \cdot C_A \cdot \left[\frac{180 \cdot d_{\lim} \cdot N}{\pi}\right]^{-0.25} \cdot \left[\left(\frac{d_{\lim}}{2\pi \cdot \omega}\right)\right]^{0.75}\right\}} = \left(\frac{1}{R}\right)^{-0.25} \cdot \left(\frac{1}{R}\right)^{0.75} \cdot R$$

$$\frac{\left(\frac{\Phi \cdot d_{\lim}}{2\pi\omega}\right)}{\left\{\left(1.8 \times 10^{-3}\right) A_{\lim} \cdot C_A \cdot \left[\frac{180 \cdot d_{\lim} \cdot N}{\pi}\right]^{-0.25} \cdot \left[\left(\frac{d_{\lim}}{2\pi \cdot \omega}\right)\right]^{0.75}\right\}} = R^{0.5}$$

The NOHD (1D-Q) can be expressed as follows.

$$R_{NOHD} = \left[\frac{\left(\frac{\Phi \cdot d_{\lim}}{2\pi\omega}\right)}{\left\{\left(1.8 \times 10^{-3}\right) \cdot \left(\frac{\pi \cdot \left(d_{\lim}\right)^2}{4}\right) \cdot C_A \cdot \left[\frac{180 \cdot d_{\lim} \cdot N}{\pi}\right]^{-0.25} \cdot \left[\left(\frac{d_{\lim}}{2\pi \cdot \omega}\right)\right]^{0.75}\right\}}\right]^2$$

$$R_{NOHD} = \left[\frac{\left(\frac{\left(7.46 \times 10^{-3}\right) \cdot (0.7)}{8\pi} \right)}{\left\{ \left(1.8 \times 10^{-3}\right) \cdot \left(\frac{\pi \cdot (0.7)^2}{4} \right) \cdot (1.445) \cdot \left[\frac{180 \cdot (0.7) \cdot (13.3)}{\pi} \right]^{-0.25} \cdot \left[\left(\frac{0.7}{8\pi} \right) \right]^{0.75} \right\}} \right]^2$$

$$R_{NOHD} = \left[\frac{\left(207.8 \times 10^{-6}\right)}{\left(1.8 \times 10^{-3}\right) \cdot (0.385) \cdot (1.445) \cdot \left[208.1 \times 10^{-3}\right] \cdot \left[68.18 \times 10^{-3}\right]} \right]^2$$

The 1D NOHD derived from fractional pulse event counts and with the conservative safety bias of the transmitted radiance is:

$$R_{NOHD} = 214 \ \ cm$$

NOHD as a Function of Mirror Rotation Rate

The NOHD $\left(1D : Q_{\lim}\right)$ associated with each available mirror rotation rate can be expressed as a function of that mirror rotation rate (ω).

$$R_{NOHD} = f(\omega)$$

$$R_{NOHD} = \left[\frac{\left(\frac{\Phi \cdot d_{\lim}}{2\pi\omega} \right)}{\left\{ \left(1.8 \times 10^{-3}\right) \cdot \left(\frac{\pi \cdot \left(d_{\lim}\right)^2}{4} \right) \cdot C_A \cdot \left[\frac{180 \cdot d_{\lim} \cdot N}{\pi} \right]^{-0.25} \cdot \left[\left(\frac{d_{\lim}}{2\pi \cdot \omega} \right) \right]^{0.75} \right\}} \right]^2$$

Excel© – **Laser Hazard 1D Model Spreadsheet** for DeltaSphere-3000 Laser Scanner.

An Excel spreadsheet was developed to model the laser hazard analysis for the DeltaSphere-3000 Laser 3D Scene Digitizer infrared laser scanner to validate previous analysis of the current condition as well as to model laser hazard for future conditions.

Spreadsheet models were developed for both the 1D and the 2D methods of the transmitted radiance determination.

The NOHD (1D-Q) was determined for the various mirror rotation rates allowed. These rotation rates are software controlled (see Excel spreadsheets Appendix 5) and are presented in Table 6. Due to transmitted area overlap partial pulse counts were used in the determination of the multiple pulse correction factor.

Table 6

Summary of NOHD $(1D:Q_{\lim})$ and Extended Source Hazard Laser Class For various Mirror Rotation Rates

Sample Density (samples/degree)	**Mirror Rotation (rev / sec)**	**NOHD (cm)**	**Extended Source Hazard Class**
5	4	131.2	1
5	8	92.8	1
5	10	83.0	1
5	16	65.6	1
6.66	4	151.4	3a
6.66	8	107.1	1
6.66	10	95.8	1
10	4	185.5	3a
10	8	131.2	1
13.3*	**4**	**214.0**	**3a**
20†	4	262.4	3a

*Default Setting
†Normally not used. (Too long a sample run).

G. **Laser Safety Eyewear**

Laser safety eyewear is required at the exit of the laser to the boundary of the ocular hazard zone. The determination of the minimum **Optical Density** (OD) of the laser safety eyewear is based on the (worst case) CW radiant emission for a ten second exposure at the laser exit (MPE_{CW}).

$$MPE_{CW} = C_A \times 10^{-3} \ {}^{w}\!/_{cm^2}$$

$$700 \ \ nm < \lambda < 1050 \ \ nm$$

$$10 \ \ \sec \le T \le 3 \times 10^4 \sec$$

Minimum Optical Density

Laser safety eyewear with a minimum optical density is to provide full protection for the worst-case condition of the laser hazard.

The worst case, although very unlikely, is the direct intrabeam exposure to the CW transmitted laser beam for 10 seconds [*ANSI Std. Z136.1-2000 (Table 4a)*].

$$OD_{\min} = \log \left[\frac{\left(\Phi / A_{\lim} \right)}{MPE} \right]$$

$$OD_{\min} = \log \left[\frac{\Phi}{MPE \cdot A_{\lim}} \right]$$

$$OD_{\min} = \log \left[\frac{\Phi}{AEL} \right]$$

$$OD_{\min} = \log \left[\frac{7.46 \times 10^{-3} \, w}{\left(1.445 \times 10^{-3} \ {}^{w}\!/_{cm^2}\right) \ \left(0.385 \ \ cm^2\right)} \right]$$

$$OD_{\min} = 1.13$$

Engineering controls shuts the laser "off" if the rotating mirror rotation rate falls below 4 revolutions per second.

H. **Extended Source Correction**

Extended source may apply to semiconductor laser diodes if the viewing angular subtend is greater than $\alpha_{\min}$ [*ANSI Std. Z136.1-1993 (8.1)*].

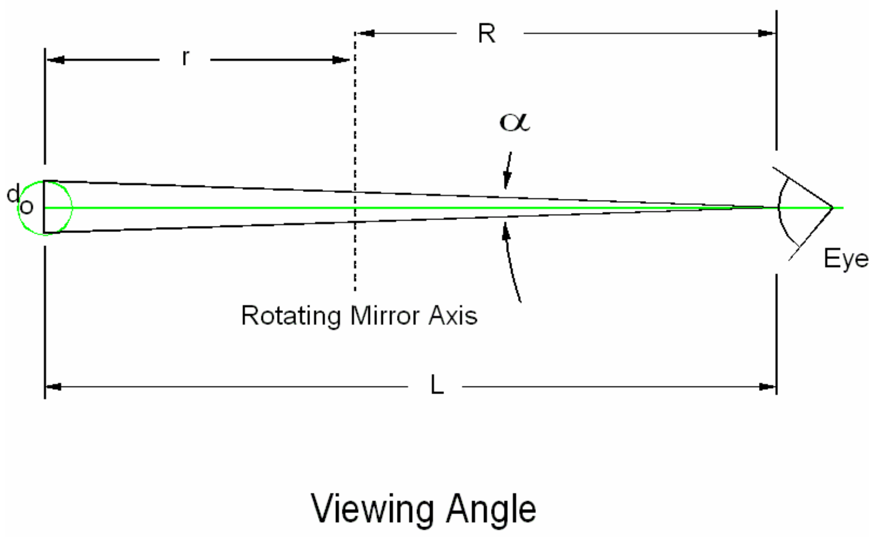


Figure 18

Viewing Angle

The **extended source correction coefficient** (C_E) applies when the **viewing angle** (α) exceeds **minimum viewing angle** ($\alpha_{\min}$), specified as 1.5 milli-radians in *ANSI Std. Z136.1-2000 – Table 6 notes*.

The viewing angle (α) is a function of the laser diode emission surface size (d_o) and the distance from the laser (L).

$$\alpha = \frac{d_o}{L}$$

The distance from the laser is the sum of the radial distance (R) from the rotating mirror and the distance from the laser to the rotating mirror (r).

$$\alpha = \frac{d_o}{r + R}$$

Extended source correction applies for all radial distances where:

$$\alpha_{\min} = \frac{d_o}{r + R} = 1.5 \times 10^{-3} radians$$

The *extended source* to *small source* crossover distance (R_X) can be determined.

$$R_X = \frac{d_o}{\alpha_{\min}} - r$$

$$R_X = \frac{0.25 \ cm}{1.5 \times 10^{-3}} - 18 \ cm$$

Crossover Distance (extended source to small source):

$$R_X = 148.7 \ cm$$

The *small source* NOHD is greater than the *extended source* to *small source* cross over distance; hence the *small source* hazard is the appropriate hazard to consider for the DeltaSphere-3000 in the “default” configuration.

V. Modified Configuration

The transmitted laser beam intensity (radiant power) was reduced by the inclusion of a Neutral Density (ND) filter of value ND0.1. A Rolyn® 80 % T filter was used to approximate a ND0.1 filter (~79%).

$$\Phi_{emitted} = \tau_{total} \cdot \Phi_{laser}$$

$$\tau_{total} = (\tau_{window}) \cdot (\tau_{filter})$$
$$\tau_{total} = (0.9325) \cdot (0.8)$$
$$\tau_{total} = 0.746$$

$$\Phi_{emitted} = (0.746) \cdot 8 \ \ mw$$

$$\Phi_{emitted} = 5.97 \ \ mw$$

The radiant power was measured (**5.72 mw**) at the window exit after the transmission filter with an **Ophir Model 2A-SH** power head (60 μw to 2 watts CW @ ± 3% accuracy error) and an Ophir Model **NOVA** digital display (calibrated in the NIR) combined system error ± 4%. The measure value is 4.2% less than the calculated value based on nominal laser power of 8 mw. Since the measured value of the radiant power was less than the calculated value for the radiant power at exit, the higher calculated value is used throughout the hazard analysis to maintain a conservative safety bias.

NOHD (1D Method)

The reduction of the emitted laser power from 7.46 mw to approximately 5.97 mw applied to the Excel 1D Model impacts the small source NOHD. The more conservative 1D small source NOHD lies somewhere between ~106.7 cm and ~133.4 cm.

$$106.7 \ \ cm < NOHD_{small \ \ source} < 133.4 \ \ cm$$

The small source NOHD is now less than the extended-source to *small-source* crossover distance as a result the *extended source correction factor* can be applied to the MPE determination and therefore also the AEL.

$$NOHD_{small \ \ source} < R_x$$

$$133.4 \ \ cm < 149 \ \ cm$$

The *extended-source* to *small-source* crossover distance was determined to be approximately 149 centimeters (page 57).

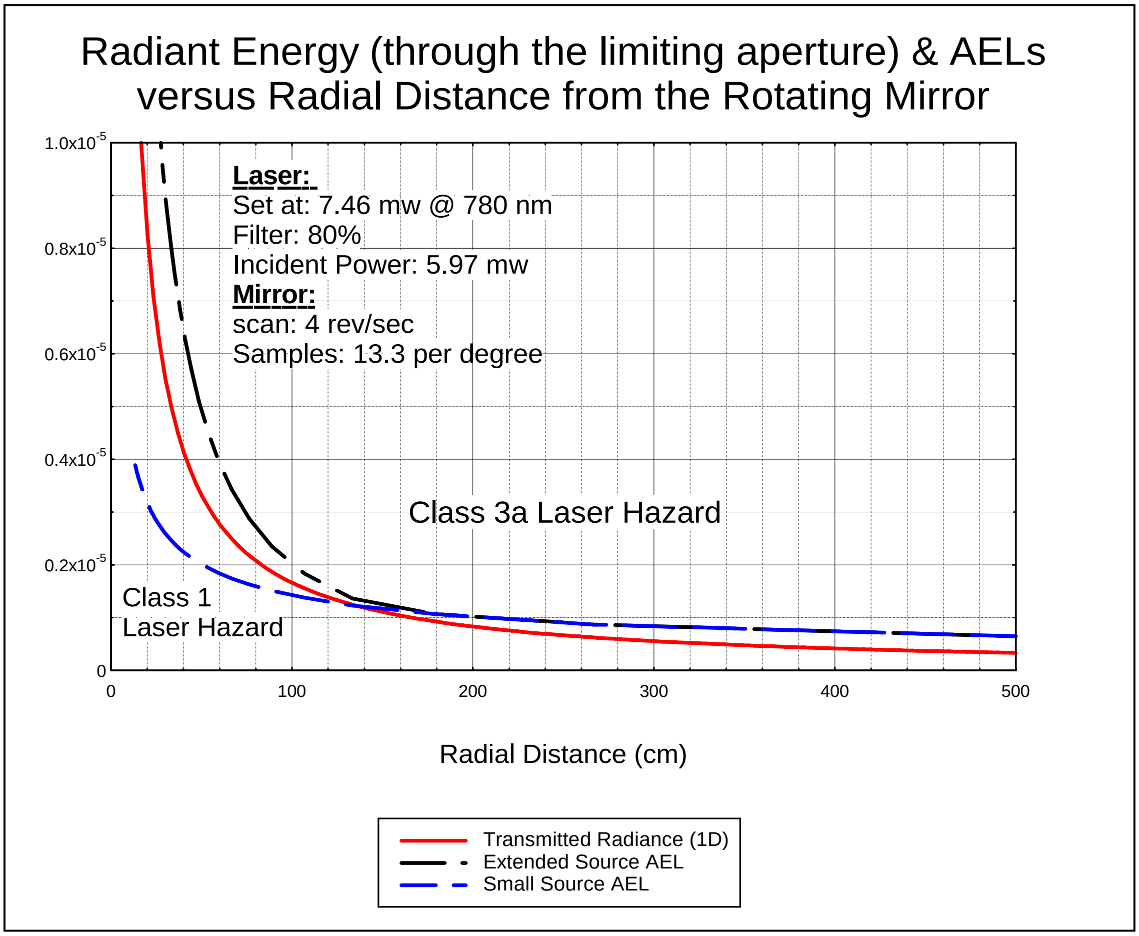


Figure 19

A plot of the radiant energy (1D) transmitted through the limiting aperture is less than the appropriate AEL for both the small source and the extended source regions.

The average "pulsed" radiant energy transmitted through the limiting aperture is below the appropriate AEL for both the *extended source* and the *small source* regions. The extend source AEL region starts at the minimum viewing radial distance, 10 centimeters, and extends to the *extended source* to *small source* crossover distance, 149 centimeters, and the *small source* AEL region applies to radial distances greater than 149 centimeters. The system with the reduced emitted laser power by the ND filter presents a Class 1 laser hazard and maybe considered "eye safe".

VI. Alternate Default Configuration

3rd Tech has suggested an alternate default configuration of the DeltaSphere-3000 Laser 3D Scene Digitizer to produce a Class 1 operation (see table 6 on page 54 for 1D approximation), where the IR version is reprogrammed (excluding 4 rev/sec at 13.3 sample density) as follows:

Mirror Rotation	**8 revolutions / second**
Sample Density	**10 samples / degree**

The current default configuration allows these operation parameters as well as other operating parameters (as indicated in table 6) administratively, through software controls, but the physical laser "shut off" is interlocked at four revolutions per second and would have to be reset to eight revolutions per second by 3rd Tech.

2D Laser Hazard Analysis for Alternate Configuration

The more conservative 1D approximation indicates an *extended source* Class 1 operation for the DeltaSphere-3000 at the alternative configuration (see table 6); however, a 2D laser hazard analysis will also be performed to complete this dual approach analysis.

The appropriate AEL and the radiant energy transmitted through the limiting aperture as a function of integral number of pulses (from the Excel spreadsheet model) that pertains to the alternate default configuration is presented in Table 7 below.

Table 7

AEL (Small Source & Extended Source) and (2D Q) Radiance
At Select Radial Distances

n	R (cm)	AEL_{SS} (nJ)	AEL_{ES} (nJ)	Q_{lim}* (nJ)
1	401.1	453	453	239
2	200.5	641	641	410
3	133.7	785	862	740
4	100.3	906	1280	999

*Transmitted radiance determined by the 2D method

~NOHD (2D method)

The NOHD lies somewhere between, approximately 100 centimeters and approximately 134 centimeters from the rotating mirror.

Radiance Through the Limiting Aperature (2D)
& small source AEL
versus Radial Distance from the Rotating Mirror
(Alternate Configuration)

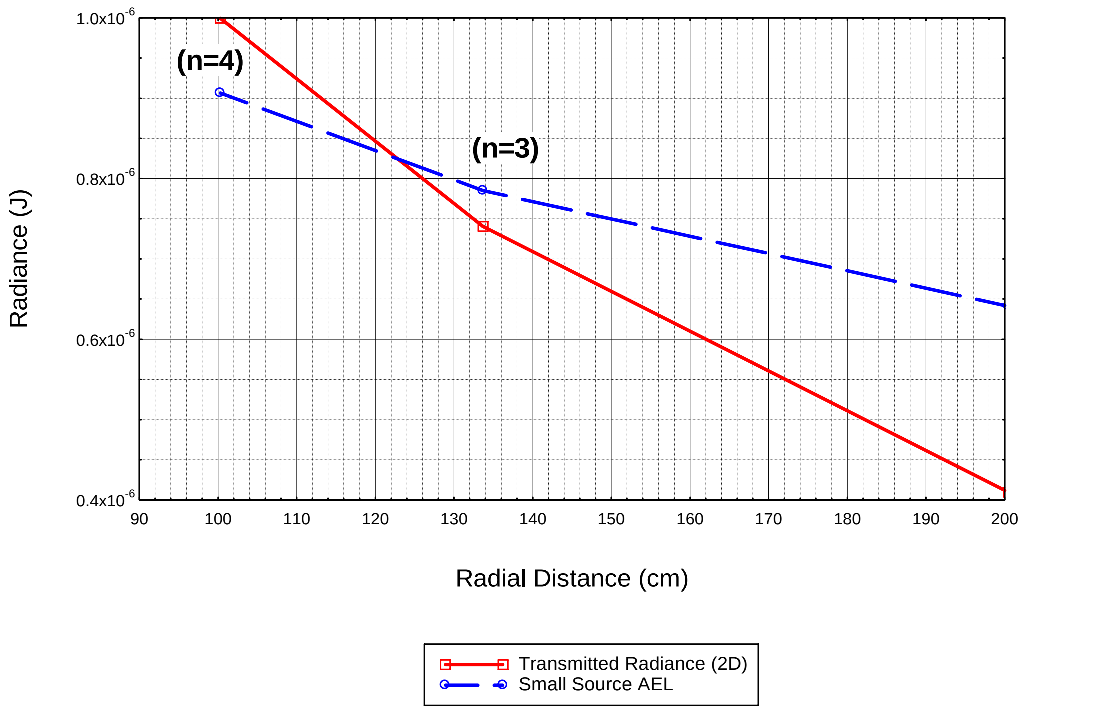


Figure 20

The plot of the radiant energy transmitted through the limiting aperture for the alternate configuration of the 3rd Tech DeltaSphere-3000 and the appropriate AEL versus the radial distance from the rotating mirror yields a small source NOHD of approximately 123 centimeters

A comparison of the plots for the radiant energy transmitted through the limiting aperture to the *small source* AEL at radial distance specific to three and four pulse events yields a *small source* NOHD of approximately 123 centimeters (figure 20).

$$small\ \ source\ \ NOHD_{alternate\ \ configuration} = \sim 123\ \ cm$$

Extended Source Applicability

The *extended source* to *small source* crossover distance had previously been calculated to be approximately 149 centimeters from the rotating mirror. Since the *small source* NOHD (~123 cm) is less than the *extended source* to *small source* crossover distance the Extended Source Correction is applicable to this system.

Extended Source Correction

The form of *extended source correction factor* is given in *ANSI Std. Z136.1-2000 (Table 6)* as:

$$C_E = \frac{\alpha}{\alpha_{\min}}$$

The viewing angle (α) was shown to be a function of the radial distance from the rotating mirror (page 56)

$$\alpha = \frac{d_o}{r+R} = \frac{d_o}{L}$$

Table 8

Extended Source Correction Factors - Alternate Configuration

n	R (cm)	L (cm)	α (radians)	α/α_{min}	C_E
1	401.1	419.1	0.6×10^{-3}	0.4	1.00
2	200.5	218.5	1.15×10^{-3}	0.8	1.00
3	133.7	151.7	1.65×10^{-3}	1.10	1.10
4	100.3	118.3	2.11×10^{-3}	1.41	1.41
5	80.2	98.2	2.55×10^{-3}	1.70	1.70
6	66.2	84.8	2.95×10^{-3}	1.96	1.96
7	57.3	75.3	3.32×10^{-3}	2.21	2.21
8	50.1	68.1	3.67×10^{-3}	2.45	2.45
9	44.6	62.6	4.00×10^{-3}	2.66	2.66
10	40.1	58.1	4.30×10^{-3}	2.66	2.66

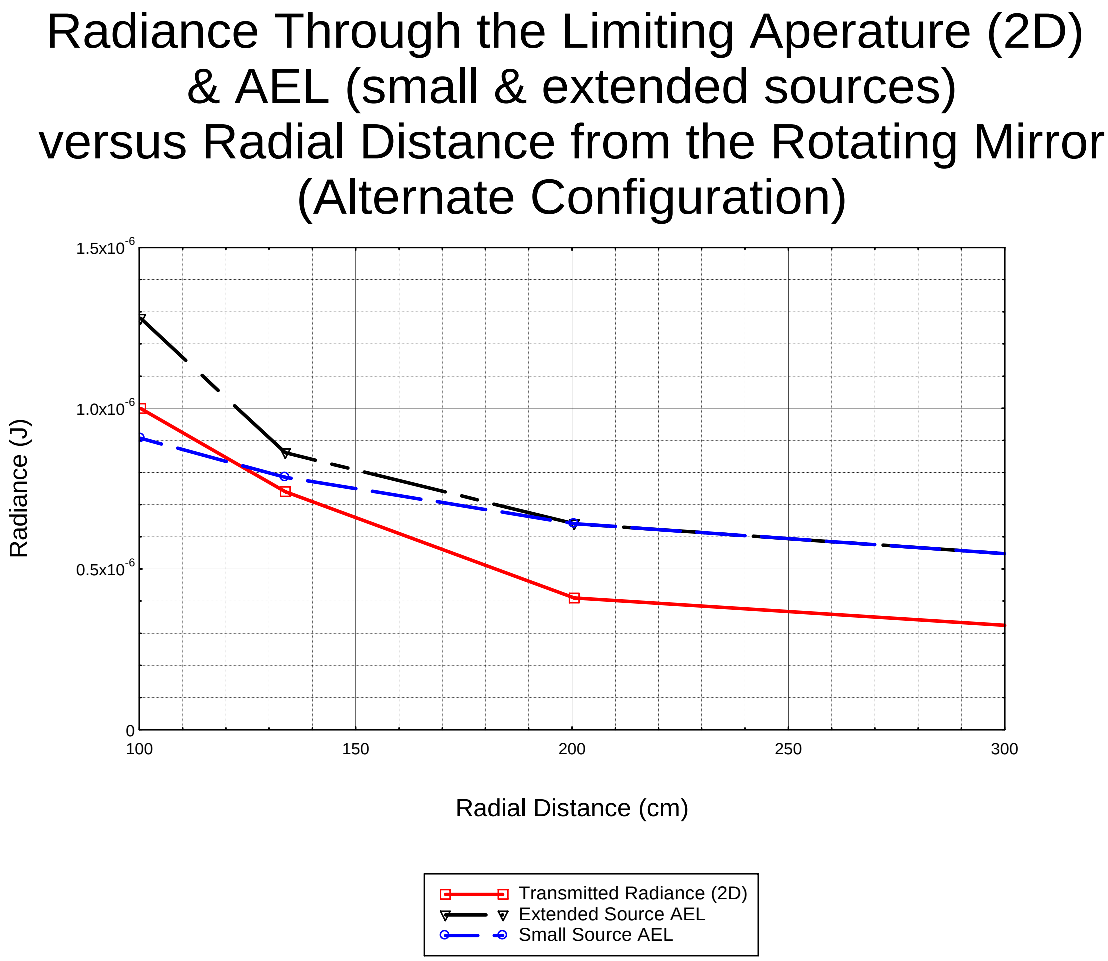


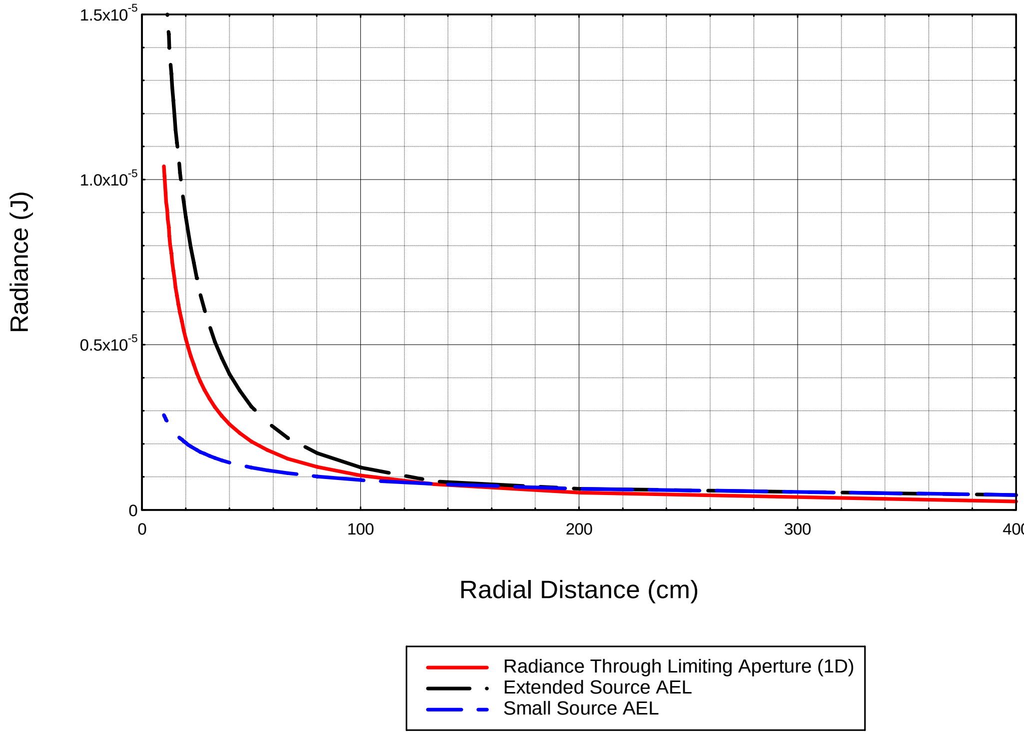
Figure 21

A plot of the radiance transmitted through the limiting aperture (2D method) and both the extended source as well as the small source AEL at the radial distances from the rotating mirror for 1, 2, 3, and 4 pulse events shows that in these cases that the radiance through the limiting aperture is less than the appropriate AEL. (Note: Although data points are presented for ~134 and ~200 centimeters; the Extended Source AEL is defined equaled to the Small Source AEL at radial distances greater than ~149 centimeters.)

2D-System Laser Hazard Class

Recall that the *extended source* to *small source* crossover distance was approximately 149 centimeters (page 57). A comparison of the radiance transmitted through the limiting aperture using the 2D method (more accurate method) to both the *small source* AEL and the *extended source* AEL at the radial distances from the rotating mirror specific to 1, 2, 3, and 4 pulse events shows that in these cases the transmitted radiance is less than the appropriate AEL and can be considered a Class 1 laser system operation.

Radiance Through Limiting Aperture (1D) for the Alternate Configuration of the Deltasphere-3000 and the AEL for Small Source and Extended Source vs Radial Distance from the Rotating Mirror



<u>Figure 22</u>

A plot of the radiance transmitted through the limiting aperture (1D) and both the extended source as well as the small source AEL as a function of the radial distances from the rotating mirror shows that in all cases the radiance through the limiting aperture is less than the appropriate AEL.

1D-System Laser Hazard Class

A comparison of the radiance transmitted through the limiting aperture using the 1D method (most conservative with regard to laser safety) to both the *small source* AEL and the *extended source* AEL as a function of the radial distance from the rotating mirror shows that in all cases the transmitted radiance is less than the appropriate AEL and can be considered a Class 1 laser operation and can be operated without restrictions, providing there is no focusing of the beam after it exits the DeltaSphere-3000.

VII. Conclusion

1. Small Source Hazard (**Initial Configuration**)

   The *small source* hazard is the appropriate hazard to consider for the laser hazard analysis (default operating conditions) of the 3rd Tech DeltaSphere-3000 Laser 3D Scene Digitizer. For the worst case, slowest allowed mirror rotation rate (4 rev/sec), the NOHD (2D Q) associated with the default operating condition is about 188 cm (from the rotating mirror). Laser safety eyewear of at least 1.13 OD is required to be worn inside this ocular hazard distance.

Mirror Rotation (Rev/Sec)	**Sampling (Samples/Degree)**	**NOHD (cm)**	**Configuration**
4	**13.3**	**~188**	**Current**
4	13.3	<133	Modified*

*Insertion of a ~80% transmission filter in the exit beam.

2. Insertion of Transmission Filter (**Modified Configuration**)

   The insertion of an approximate 80 percent transmission filter at 780 nm reduces the scanning laser beam power to where the NOHD is less than the extended source to *small source* crossover distance. This allows for the *Extended Source Correction* to be applied. The DeltaSphere-3000 laser output presents a Class 1 laser system operation hazard even though it contains an embedded Class 3b laser.

3. **Alternate Configuration (8 rev/sec @ 10 samples/degree)**

   The alternate default configuration of the IR scanner suggested by 3rd Tech [8 mirror revolutions per second (interlocked minimum mirror rotation rate) and a default sample density of 10 samples per degree], yields a *small source* NOHD (~123 cm), which is less than the *extended source* to *small source* crossover distance. With the Extended Source Correction applied, the alternate default configuration of the 3rd Tech DeltaSphere-3000 presents a Class 1 system operation hazard with an embedded Class 3b IR laser.

4. **Personnel Exclusion Zone**

   It is prudent, whenever possible, to maintain a personnel exclusion zone about the scanner equal to the *small source* NOHD. Additionally, take steps to insure that there are no focusing optics between the scanner and involved personnel.

VIII. **Appendix: 1 (Single Scan Transmission)**

In the radial distance range where: $R_1 \le R < R_{w=d_{\lim}} = 882\ cm$

The shortest radial distance (R_1) from the rotating mirror where, at most, one and only one scan (pulse) is transmitted through the rotating mirror.

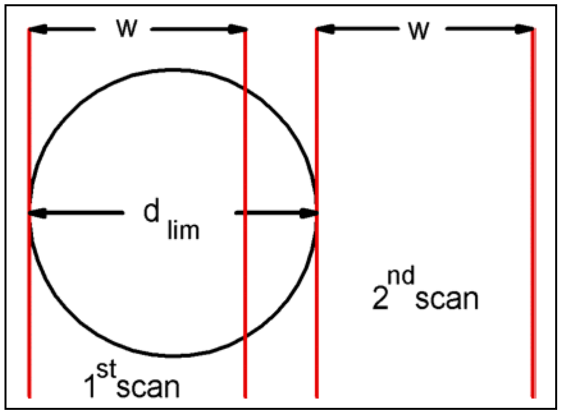


Figure 23

The shortest radial distance (R_1) where at most one and only one laser scan is transmitted through the limiting aperture.

Beam Area Transmitted Through the Limiting Aperture For A Single Scan

Worst case the transmitted scan beam area is centered on the limiting aperture.

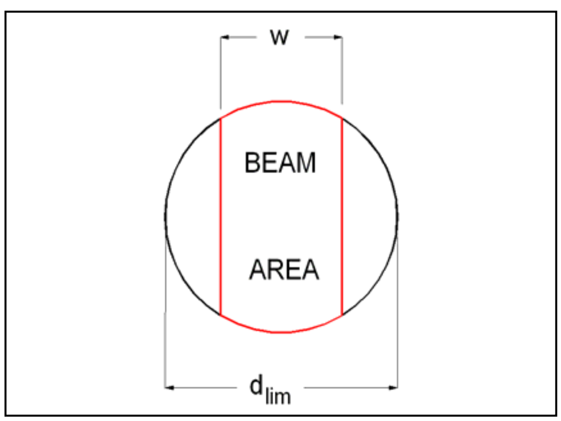


Figure 24

The cross sectional area of the laser beam transmitted through the limiting aperture.

The area of the limiting aperture $(d_{\lim})$ is:

$$A_{\lim} = \frac{\pi}{4}(d_{\lim})^2$$

The value of the limiting aperture $(d_{\lim})$ is presented in *ANSI Std. Z136.1-2000 (Table 8).*

Component Areas of the Transmitted Beam Area

For radial distances where the cross sectional area (A_τ) of the laser beam (transmitted through the limiting aperture) is less than the area of the limiting aperture the transmitted beam area can be shown to be the sum of component areas.

$$A_\tau < A_{\lim}$$

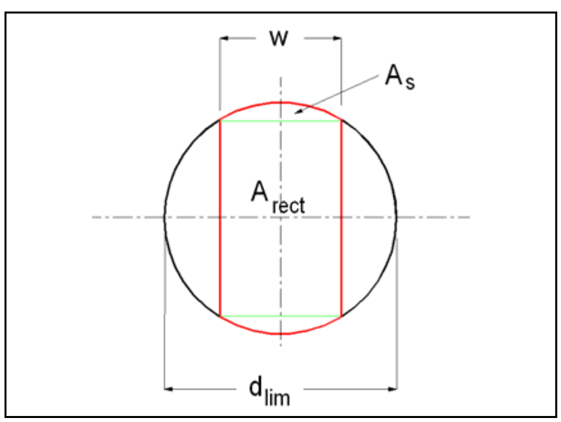


Figure 25

The cross sectional area of the laser beam transmitted through the limiting aperture as a composite of several component areas.

The cross sectional area of the laser beam transmitted through the limiting aperture can be equated to the sum of the composite areas.

$$A_{\tau} = 2A_{s} + A_{rect}$$

Wedge Area (pie shape)

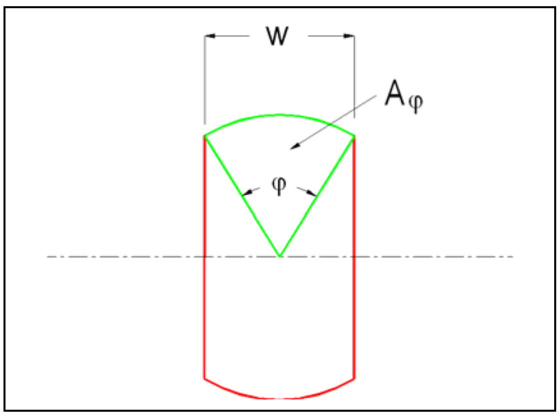


Figure 26

The cross section area of the transmitted laser beam through the limiting aperture is depicted with a pie shaped wedge area with its origin at the beam and limiting aperture center.

The wedge area (A_{φ}) can be expressed as the product of the area of the limiting aperture $(A_{\lim})$ and the ratio of the wedge angle (φ) to the complete circle (360°).

$$A_{\varphi} = A_{\lim}\left(\frac{\varphi}{360^{\circ}}\right)$$

Wedge Composite Areas

This pie shaped wedge area can be constructed of composite areas as depicted in the figure 27.

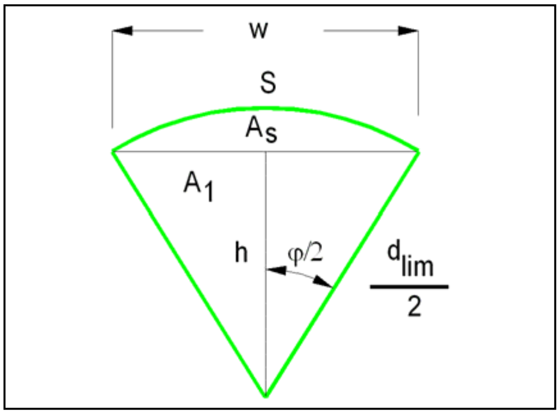


Figure 27

The pie shaped wedged area can be constructed of component areas.

The wedge (pie shaped) area (A_φ) is constructed of the composite areas, depicted as a chord-arc area (A_s) and two (equal) right triangle areas (A_1).

$$A_\varphi = 2A_1 + A_s$$

Determination of the half wedge angle

With reference to figure 27, the sine of the wedge half angle is:

$$\sin\left(\frac{\varphi}{2}\right) = \left(\frac{w/2}{d_{\lim}/2}\right) = \frac{w}{d_{\lim}}$$

$$\sin\left(\frac{\varphi}{2}\right) = \frac{w}{d_{\lim}}$$

$$\frac{\varphi}{2} = \sin^{-1}\left(\frac{w}{d_{\lim}}\right)$$

Determination of the Wedge Angle

The wedge angle (φ) can be expressed as:

$$\varphi = 2\sin^{-1}\left(\frac{w}{d_{\lim}}\right)$$

Determination of the Triangular Area

The height of the triangle (A_1) can be expressed as:

$$h = \left(\frac{d_{\lim}}{2}\right)\cos\left(\frac{\varphi}{2}\right)$$

$$h = \left(\frac{d_{\lim}}{2}\right)\cos\left(\frac{2\sin^{-1}\left(\frac{w}{d_{\lim}}\right)}{2}\right)$$

The area of the triangle (A_1):

$$A_1 = \frac{1}{2}h\cdot\left(\frac{w}{2}\right) = \frac{1}{4}h\cdot w$$

$$A_1 = \frac{w}{4}\cdot\left(\frac{d_{\lim}}{2}\right)\cos\left(\frac{\varphi}{2}\right)$$

$$A_1 = \frac{d_{\lim}\cdot w}{8}\cdot\cos\left(\frac{2\sin^{-1}\left(\frac{w}{d_{\lim}}\right)}{2}\right)$$

Recall that the laser beam width can be expressed as a function of the radial distance from the rotating mirror (page 11).

The triangular area can now be expressed as a function of the radial distance from the rotating mirror.

$$A_1 = \frac{d_{\lim} \cdot \{d_o + \theta(r+R)\}}{8} \cdot \cos\left(\frac{2\sin^{-1}\left(\frac{\{d_o + \theta(r+R)\}}{d_{\lim}}\right)}{2}\right)$$

Determination of the Arc - Chord Area

The arc – chord area (A_s) is the difference of the wedge area and the triangular areas.

$$A_s = A_\varphi - 2A_1$$

$$A_s = A_{\lim}\left(\frac{\varphi}{360^\circ}\right) - 2\left[\frac{d_{\lim} \cdot \{d_o + \theta(r+R)\}}{8} \cdot \cos\left(\frac{2\sin^{-1}\left(\frac{\{d_o + \theta(r+R)\}}{d_{\lim}}\right)}{2}\right)\right]$$

$$A_s = A_{\lim}\left(\frac{2\sin^{-1}\left(\frac{w}{d_{\lim}}\right)}{360^\circ}\right) - 2\left[\frac{d_{\lim} \cdot \{d_o + \theta(r+R)\}}{8} \cdot \cos\left(\frac{2\sin^{-1}\left(\frac{\{d_o + \theta(r+R)\}}{d_{\lim}}\right)}{2}\right)\right]$$

$$A_s = A_{\lim}\left(\frac{2\sin^{-1}\left(\frac{\{d_o + \theta(r+R)\}}{d_{\lim}}\right)}{360^\circ}\right) - \frac{d_{\lim} \cdot \{d_o + \theta(r+R)\}}{4} \cdot \cos\left(\frac{2\sin^{-1}\left(\frac{\{d_o + \theta(r+R)\}}{d_{\lim}}\right)}{2}\right)$$

$$A_s = A_{\lim}\left(\frac{2\sin^{-1}\left(\frac{\{d_o+\theta(r+R)\}}{d_{\lim}}\right)}{360^\circ}\right) - \frac{d_{\lim}\cdot\{d_o+\theta(r+R)\}}{4}\cdot\cos\left(\sin^{-1}\left(\frac{\{d_o+\theta(r+R)\}}{d_{\lim}}\right)\right)$$

Determination of the Rectangular Area

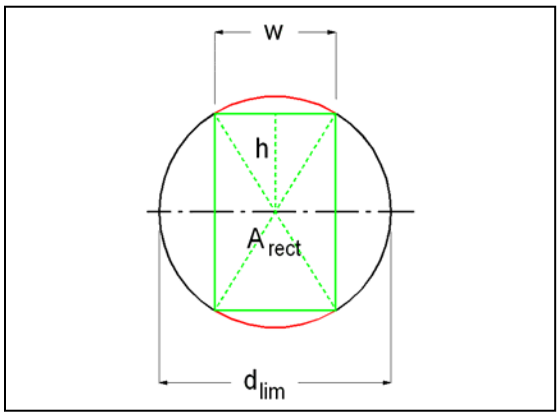


Figure 28

The solid green line shows the boundary of the rectangular area.

The area of the rectangle (A_{rect}) is the product of the combined heights and the width.

$$A_{rect} = 2h\cdot w$$

$$A_{rect} = 2\left[\left(\frac{d_{\lim}}{2}\right)\cos\left(\frac{2\sin^{-1}\left(\frac{w}{d_{\lim}}\right)}{2}\right)\right]\cdot w$$

$$A_{rect} = d_{\lim} \cdot \cos\left(\sin^{-1}\left(\frac{\{d_o + \theta(r+R)\}}{d_{\lim}} \right) \right) \cdot \{d_o + \theta(r+R)\}$$

The rectangular area can be expressed as a function of the radial distance from the rotating mirror.

$$A_{rect} = d_{\lim} \cdot \{d_o + \theta(r+R)\} \cdot \cos\left(\sin^{-1}\left(\frac{\{d_o + \theta(r+R)\}}{d_{\lim}} \right) \right)$$

Cross Sectional Beam Area Transmitted through Limiting Aperture

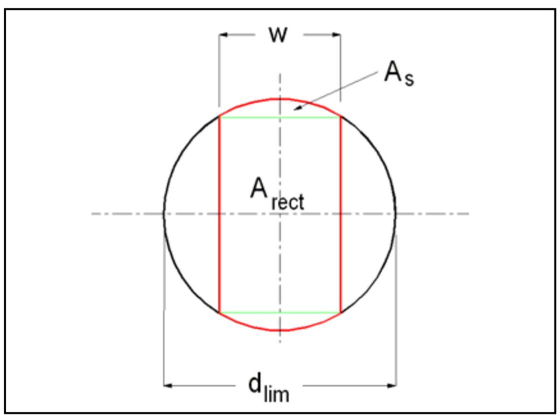


Figure 29

The cross sectional area of the laser beam transmitted through the limiting aperture for beam widths less than the limiting aperture.

The cross sectional area of the laser beam transmitted (A_τ) through the limiting aperture is the sum of the rectangular area (A_{rect}) and the chord-arc area (A_s).

$$A_\tau = 2A_s + A_{rect}$$

$$A_\tau = 2\left[A_{\lim}\left(\frac{2\sin^{-1}\left(\frac{\{d_o+\theta(r+R)\}}{d_{\lim}}\right)}{360^\circ}\right) - \frac{d_{\lim}\cdot\{d_o+\theta(r+R)\}}{4}\cdot\cos\left(\sin^{-1}\left(\frac{\{d_o+\theta(r+R)\}}{d_{\lim}}\right)\right)\right]$$
$$+ d_{\lim}\cdot\{d_o+\theta(r+R)\}\cdot\cos\left(\sin^{-1}\left(\frac{\{d_o+\theta(r+R)\}}{d_{\lim}}\right)\right)$$

The cross sectional area of the laser beam transmitted through the limiting aperture as a function of the radial distance from the rotating mirror can be expressed as:

$$A_\tau = 2A_{\lim}\left(\frac{\sin^{-1}\left(\frac{\{d_o+\theta(r+R)\}}{d_{\lim}}\right)}{180^\circ}\right) - \frac{d_{\lim}\cdot\{d_o+\theta(r+R)\}}{2}\cdot\cos\left(\sin^{-1}\left(\frac{\{d_o+\theta(r+R)\}}{d_{\lim}}\right)\right)$$
$$+ d_{\lim}\cdot\{d_o+\theta(r+R)\}\cdot\cos\left(\sin^{-1}\left(\frac{\{d_o+\theta(r+R)\}}{d_{\lim}}\right)\right)$$

$$A_\tau = A_{\lim}\left(\frac{\sin^{-1}\left(\frac{\{d_o+\theta(r+R)\}}{d_{\lim}}\right)}{90^\circ}\right) - \frac{d_{\lim}\cdot\{d_o+\theta(r+R)\}}{2}\cdot\cos\left(\sin^{-1}\left(\frac{\{d_o+\theta(r+R)\}}{d_{\lim}}\right)\right)$$
$$+\,d_{\lim}\cdot\{d_o+\theta(r+R)\}\cdot\cos\left(\sin^{-1}\left(\frac{\{d_o+\theta(r+R)\}}{d_{\lim}}\right)\right)$$

The scan area at the radial distance, R=533.4 cm:

$$A_{scan} = 2\pi R\cdot w$$

$$A_{scan} = 2\pi(533.4\ cm)\cdot(0.526\ cm)$$

$$A_{scan} = 1762\ cm^2$$

The radiant energy (2D method) transmitted through the limiting aperture at the radial distance of approximately 533 centimeters can be calculated as follows.

$$Q_{\lim} = \left(\frac{\Phi}{\omega}\right)\cdot\left[\frac{A_\tau}{A_{scan}}\right]$$

$$Q_{\lim_{R=533.4cm}} = \left(\frac{7.46\times10^{-3}\,watts}{4\,{}^{rev}\!/_{\sec}}\right)\cdot\left(\frac{0.33\ cm^2-rev}{1762\ cm^2}\right)$$

$$Q_{\lim_{R=533.4cm}} = 349\times10^{-9}\ J$$

Appendix 2: Two Scan Transmissions

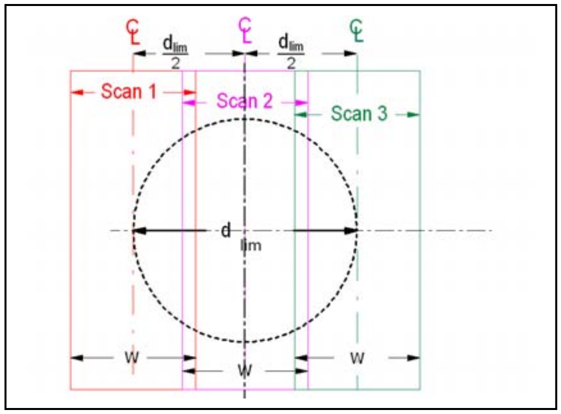


Figure 30

The spacing between the centerlines of two successive mirror scans is equal to exactly one half the diameter of the limiting aperture.

At the radial distance of approximately 267 centimeters from the rotating mirror the spacing between center-lines of the scans are equal to exactly half the limiting aperture.

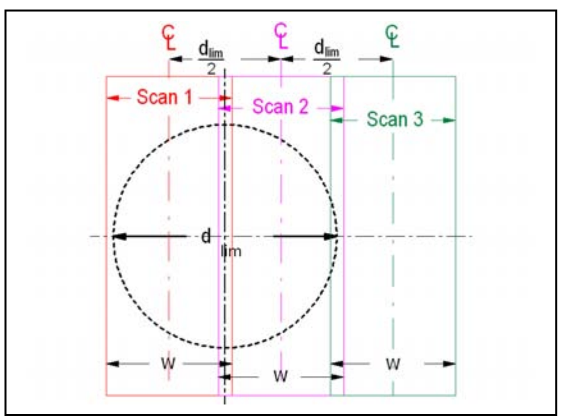


Figure 31

Overlapping mirror scans at the radial distance, which allows just two such mirror scans to transmit through the limiting aperture.

Placing the centerline of the limiting aperture at the centerline of the over-lapped scan area allows for two equal mirror scan transmission areas plus two small residual areas from adjacent scans. The small transmitted scan area from the adjacent scan complicates the determination of the radiant pulse energies used in the laser hazard analysis.

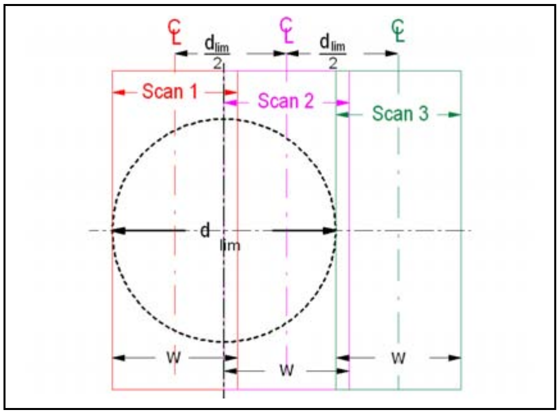


Figure 32

The alignment of the limiting aperture's centerline to the start of the second scan produces only two, if two unequaled transmitted areas.

The determination of the radiant transmitted energy at this radial distance can be simplified. The transmitted radiant energy can be approximated from the area of the largest transmitted scan area. The two unequal scan areas are set equal to the larger area (since the area contributed by the adjacent area, prior to "scan 1" would be equal to area of "scan 2" outside the aperture).

This simplification and approximation of areas yields a higher transmitted radiant energy for the second scan. The subsequent laser hazard analysis based on the (transmitted) radiant energy determined by this approximation method will necessarily yield results with a slight conservative safety bias, since it will be assumed that both transmitted pulses will be equal to the largest of the transmitted pulse radiance.

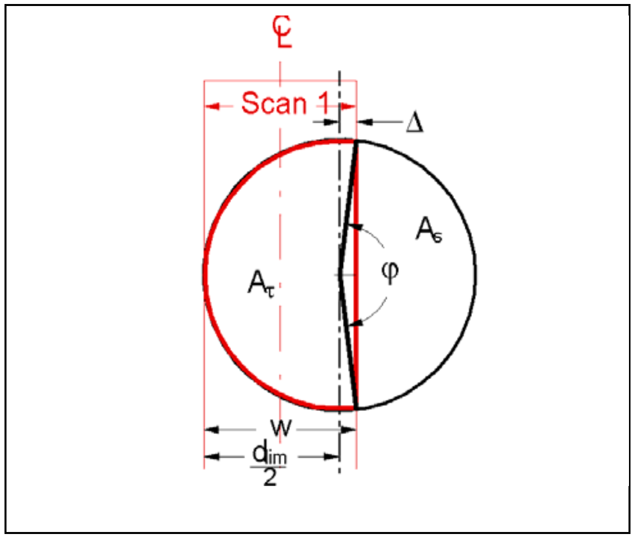


Figure 33

The transmitted radiant energy can be approximated from the transmitted scan area.

The transmitted scan area can be determined by:

$$A_\tau = A_{\lim} - A_s$$

The "pie shaped area" can be calculated as follows:

$$A_\varphi = A_{\lim}\left(\frac{\varphi}{360}\right)$$

The arc-chord area is the difference between the "pie shaped area" and the sum of the two right triangle areas.

$$A_s = A_\varphi - 2A_\Delta$$

$$A_s = A_\varphi - 2\left[\left(\frac{\Delta}{2}\right)\cdot\left(\frac{d_{\lim}}{2}\right)\cdot\sin\left(\frac{\varphi}{2}\right)\right]$$

$$A_s = A_\varphi - \Delta\cdot\left(\frac{d_{\lim}}{2}\right)\sin\left(\frac{\varphi}{2}\right)$$

$$\frac{\varphi}{2} = \cos^{-1}\left[\frac{\Delta}{\left(\frac{d_{\lim}}{2}\right)}\right]$$

$$A_s = A_\varphi - \Delta \cdot \left(\frac{d_{\lim}}{2}\right)\sin\left(\frac{\cos^{-1}\left(\frac{2\Delta}{d_{\lim}}\right)}{2}\right)$$

The " Δ " is difference between the beam width and half the limiting aperture.

$$\Delta = w - \frac{d_{\lim}}{2}$$

$$\Delta = d_o + \theta(r + R) - \frac{d_{\lim}}{2}$$

$$A_s = A_\varphi - \left(d_o + \theta(r + R) - \frac{d_{\lim}}{2}\right) \cdot \left(\frac{d_{\lim}}{2}\right)\sin\left(\frac{\cos^{-1}\left(\frac{2\left(d_o + \theta(r + R) - \frac{d_{\lim}}{2}\right)}{d_{\lim}}\right)}{2}\right)$$

$$A_s = A_{\lim}\left(\frac{\varphi}{360}\right) - \left(d_o + \theta(r+R) - \frac{d_{\lim}}{2}\right)\cdot\left(\frac{d_{\lim}}{2}\right)\sin\left(\frac{\cos^{-1}\left(\frac{2\left(d_o + \theta(r+R) - \frac{d_{\lim}}{2}\right)}{d_{\lim}}\right)}{2}\right)$$

$$A_s = A_{\lim}\left(\frac{2\cdot\cos^{-1}\left(\frac{2(d_o + \theta(r+R))}{d_{\lim}} - 1\right)}{360}\right) - \left(d_o + \theta(r+R) - \frac{d_{\lim}}{2}\right)\cdot\sin\left(\frac{\cos^{-1}\left(\frac{2(d_o + \theta(r+R))}{d_{\lim}} - 1\right)}{2}\right)$$

At the radial distance R=266.7 cm:

$$A_s = \left(0.385\ cm^2\right)\cdot\left(\frac{2\cdot\cos^{-1}\left(\frac{2\left(0.25 + 0.5\times10^{-3}(18+266.7)\right)}{0.7} - 1\right)}{360}\right) - \left(0.25 + 0.5\times10^{-3}(18+266.7) - \frac{0.7}{2}\right)cm\cdot\left(\frac{0.7cm}{2}\right)\sin\left(\frac{\cos^{-1}\left(\frac{2\left(0.25 + 0.5\times10^{-3}(18+266.7)\right)}{0.7} - 1\right)}{2}\right)$$

$$A_s = 0.163\ cm^2$$

The transmitted area of the mirror scan is:

$$A_\tau = A_{\lim} - A_s$$

$$A_\tau = 0.385\ cm^2 - 0.163\ cm^2$$

$$A_\tau = 0.222\ cm^2$$

The scan area at the radial distance, R=266.7 cm:

$$A_{scan} = 2\pi R \cdot w$$

$$w = d_o + \theta(r+R) = 0.25\ cm + 0.5\times10^{-3}(18\ cm + 266.7\ cm)$$
$$w = 0.392\ cm$$

$$A_{scan} = 2\pi(266.7\ cm)\cdot(0.392\ cm)$$

$$A_{scan} = 657.5\ cm^2$$

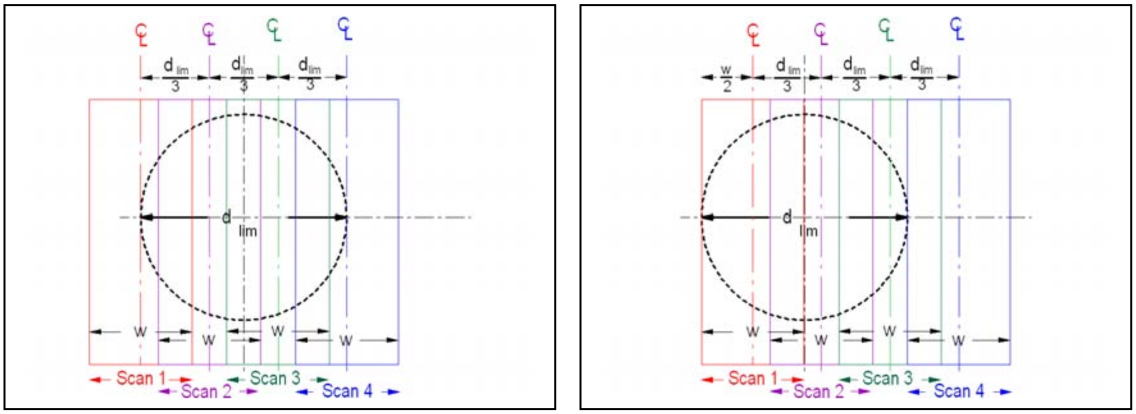
The radiant energy transmitted through the limiting aperture at the radial distance of approximately 267 centimeters can be calculated as follows.

$$Q_{\lim} = \left(\frac{\Phi}{\omega}\right)\cdot\left[\frac{A_\tau}{A_{scan}}\right]$$

$$Q_{\lim_{R=266.7\,cm}} = \left(\frac{7.46\times10^{-3} watts}{4\, {rev}/{\sec}}\right)\cdot\left(\frac{0.222\ cm^2 - rev}{658\ cm^2}\right)$$

$$Q_{\lim_{R=266.7\,cm}} = 629.7\times10^{-9}\ J$$

Appendix 3: Three Scan Transmissions

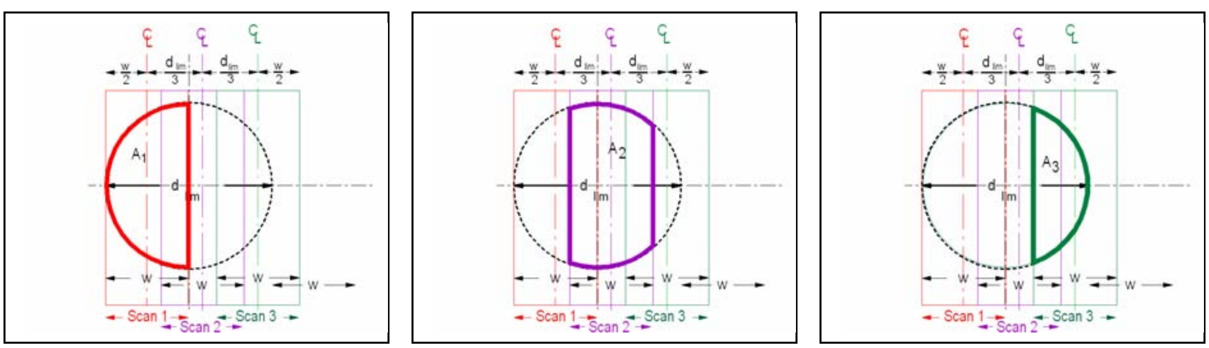


(a) (b)

Figure 34

At a radial distance of ~178 cm the centerlines of three mirror scans are transmitted through the limiting aperture (a). Aligning the edge of the limiting aperture at the edge of the first can (b) yields three unequaled areas of the transmitted scans.

At a radial distance of ~178 cm which allows the transmission of three, unequal and somewhat over lapping mirror scans areas through the limiting aperture.



(a) (b) (c)

Figure 35

The areas of transmitted scans (a) first scan, (b) second scan, and (c) third scan

From an inspection of the transmitted areas (figure 35) for the three mirror-scans the area of the third mirror scan (c) is less than the first two (a) and (b) and need not be evaluated. The largest transmitted area will determine the value to be used for the transmitted radiant energy of all three of the scan pulses.

Area of 1st Mirror Scan

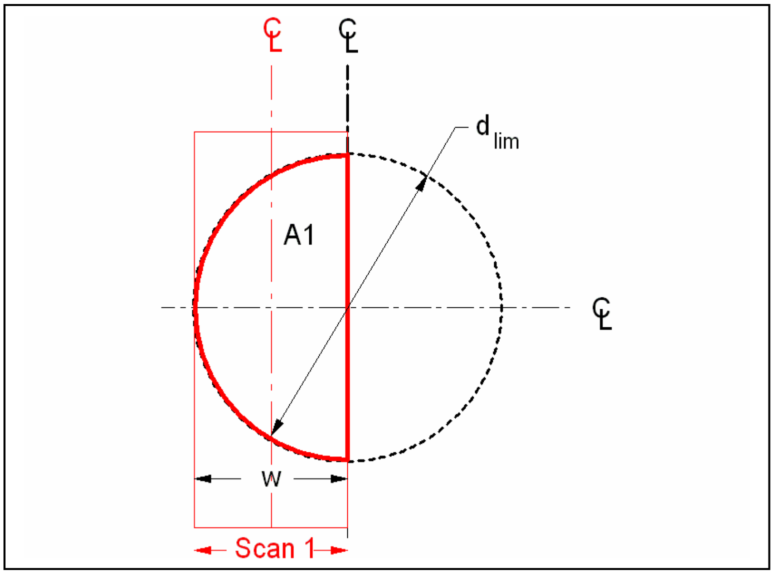


Figure 36

The transmitted area of the first scan is approximately equal to half the area of the limiting aperture.

The beam-width at a radial distance of 177.8 centimeters (from the rotating mirror) can be calculated as follows:

$$w = 0.25\ cm + \left(0.5 \times 10^{-3}\right) \cdot \left[18\ cm + 177.8\ cm\right]$$

$$w = 0.3479\ cm$$

The beam-width of the first mirror scan transmitted through the limiting aperture is approximately equal to half the limiting aperture.

$$w \approx \frac{d_{\lim}}{2}$$

$$0.3479\ cm \approx 0.35\ cm$$

The transmitted area of the first mirror scan is approximately equal to half the area of the limiting area.

$$A_1 \approx \frac{A_{\text{lim}}}{2} \approx \frac{0.385\ cm^2}{2} \approx 0.1925\ cm^2$$

Area of 2nd Mirror Scan

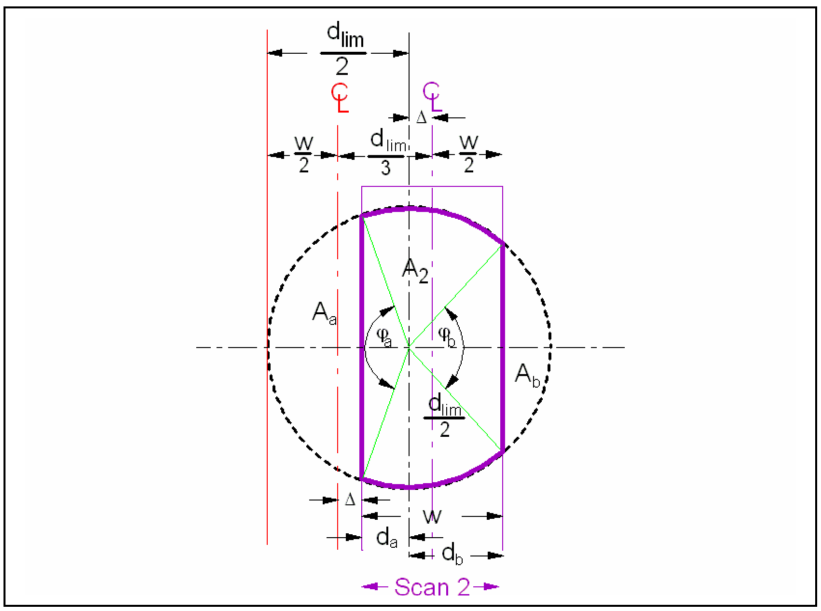


Figure 37

The transmitted area of the second scan appears to be the larger, of the three transmitted scan areas.

With reference to figure 37 the following can be derived.

$$\frac{d_{\text{lim}}}{2} + \Delta = \frac{d_{\text{lim}}}{3} + \frac{w}{2}$$

$$\Delta = \left(\frac{d_{\text{lim}}}{3} + \frac{w}{2}\right) - \frac{d_{\text{lim}}}{2}$$

$$\Delta = \left(\frac{0.7\ cm}{3} + \frac{0.3479\ cm}{2}\right) - \frac{0.7\ cm}{2}$$

$$\Delta = 0.05728\ cm$$

The “a” pie shape dimensions are:

$$d_a = \frac{w}{2} - \Delta$$

$$d_a = \frac{0.3479\ cm}{2} - 0.05728\ cm$$

$$d_a = 0.1167\ cm$$

Determination of the “a” pie shape **wedge half angle**:

$$\frac{\varphi_a}{2} = \cos^{-1}\left[\frac{d_a}{\left(\frac{d_{\lim}}{2}\right)}\right] = \cos^{-1}\left[\frac{2 \cdot d_a}{d_{\lim}}\right]$$

$$\frac{\varphi_a}{2} = \cos^{-1}\left[\frac{2 \cdot (0.1167\ cm)}{0.7\ cm}\right]$$

$$\frac{\varphi_a}{2} = 70.53^\circ$$

Determination of the “a” pie shape **wedge angle**:

$$\varphi_a = (2) \cdot (70.53^\circ)$$

$$\varphi_a = 141.1^\circ$$

The area of the “a” pie shape $\left(A_{\varphi_a}\right)$ as a proportion of the area limiting aperture:

$$A_{\varphi_a} = A_{\lim} \cdot \left(\frac{\varphi_a}{360^\circ}\right)$$

$$A_{\varphi_a} = \left(0.385\ cm^2\right) \cdot \left(\frac{141.1^\circ}{360^\circ}\right)$$

$$A_{\varphi_a} = 0.1508\ cm^2$$

The area of the two “a” pie shape isosceles triangles can be expressed as:

$$A_{\Delta_a} = \left(\frac{1}{2}\right) \cdot d_a \cdot \left(\frac{d_{\lim}}{2}\right) \cdot \sin\left(\frac{\varphi_a}{2}\right)$$

The sum of the two triangular areas is:

$$2A_{\Delta_a} = d_a \cdot \left(\frac{d_{\lim}}{2}\right) \cdot \sin\left(\frac{\varphi_a}{2}\right)$$

$$2A_{\Delta_a} = \left(0.1167\ cm\right) \cdot \left(\frac{0.7\ cm}{2}\right) \cdot \sin\left(70.53^\circ\right)$$

$$2A_{\Delta_a} = 0.03851\ cm^2$$

The arc-chord area of the “a” pie shape is:

$$A_a = A_{\varphi_a} - 2A_{\Delta_a}$$

$$A_a = 0.1508\ cm^2 - 0.03851\ cm^2$$

$$A_a = 0.1124\ cm^2$$

The "b" pie shape dimensions are:

$$d_b = \frac{w}{2} + \Delta$$

$$d_b = \frac{0.3479\ cm}{2} + 0.05728\ cm$$

$$d_b = 0.2312\ cm$$

Determination of the "b" pie shaped **wedge half angle**:

$$\frac{\varphi_b}{2} = \cos^{-1}\left[\frac{d_b}{\left(\frac{d_{\lim}}{2}\right)}\right] = \cos^{-1}\left[\frac{2 \cdot d_b}{d_{\lim}}\right]$$

$$\frac{\varphi_b}{2} = \cos^{-1}\left[\frac{2 \cdot (0.2312\ cm)}{0.7\ cm}\right]$$

$$\frac{\varphi_b}{2} = 48.65^\circ$$

Determination of the "b" pie shaped **wedge angle**:

$$\varphi_b = 2 \cdot 48.65^\circ$$

$$\varphi_b = 97.3^\circ$$

The determination of the "b" pie shaped area (A_{φ_b}) is as follows:

$$A_{\varphi_b} = A_{\lim} \cdot \left(\frac{\varphi_b}{360^\circ}\right)$$

$$A_{\varphi_b} = (0.385\ cm^2) \cdot \left(\frac{97.3^\circ}{360^\circ}\right)$$

$$A_{\varphi_b} = 0.1040 \ cm^2$$

The area of the two “b” side isosceles triangles can be expressed as:

$$A_{\Delta b} = \left(\frac{1}{2}\right) \cdot d_b \cdot \left(\frac{d_{\lim}}{2}\right) \cdot \sin\left(\frac{\varphi_b}{2}\right)$$

The sum of the two triangular areas:

$$2A_{\Delta_b} = d_b \cdot \left(\frac{d_{\lim}}{2}\right) \cdot \sin\left(\frac{\varphi_b}{2}\right)$$

$$2A_{\Delta_b} = (0.2312 \ cm) \cdot \left(\frac{0.7 \ cm}{2}\right) \cdot \sin(48.65^\circ)$$

$$2A_{\Delta_b} = 0.06075 \ cm^2$$

$$A_b = A_{\varphi_b} - 2A_{\Delta_b}$$

$$A_b = 0.1040 \ cm^2 - 0.06075 \ cm^2$$

$$A_b = 0.04325 \ cm^2$$

The transmission area of the second scan $(A_{\tau 2})$ can be determined as follows:

$$A_{\tau 2} = A_{\lim} - (A_a + A_b)$$

$$A_{\tau 2} = (0.385 \ cm^2) - (0.1123 \ cm^2 + 0.04325 \ cm^2)$$

$$A_{\tau 2} = 0.2293 \ cm^2$$

The scan area at the radial distance, R=177.8 cm:

$$A_{scan} = 2\pi R \cdot w$$

$$w = d_o + \theta(r+R) = 0.25\ cm + 0.5\times10^{-3}(18\ cm + 177.8\ cm)$$
$$w = 0.348\ cm$$

$$A_{scan} = 2\pi(177.8\ cm)\cdot(0.348\ cm)$$

$$A_{scan} = 388.7\ cm^2$$

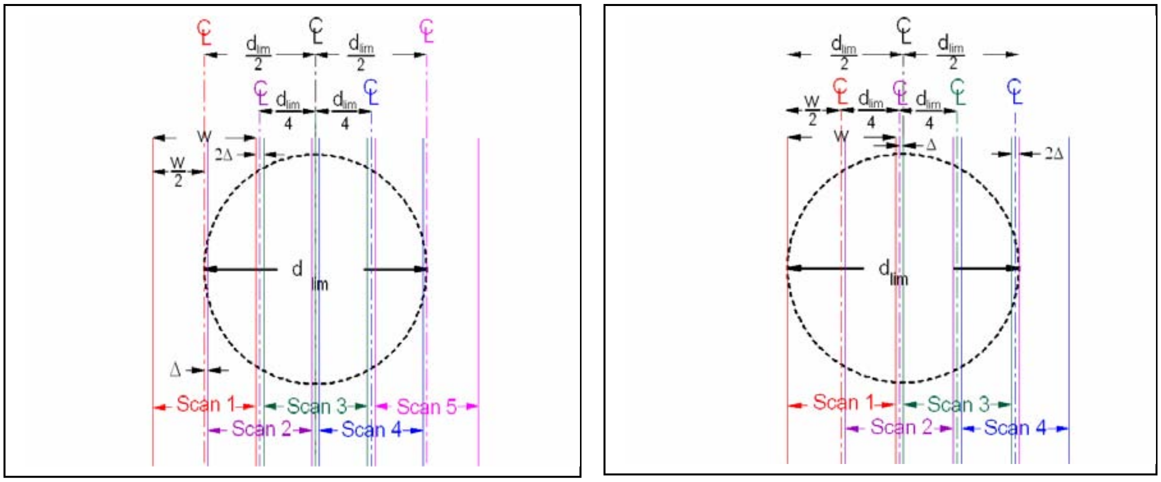
The radiant energy (2D method) transmitted through the limiting aperture at the radial distance of approximately 178 centimeters can be calculated as follows.

$$Q_{\lim} = \left(\frac{\Phi}{\omega}\right)\cdot\left[\frac{A_\tau}{A_{scan}}\right]$$

$$Q_{\lim_{R=177.8cm}} = \left(\frac{7.46\times10^{-3}\,watts}{4\,{}^{rev}\!/_{\sec}}\right)\cdot\left(\frac{0.2293\ cm^2 - rev}{388.7\ cm^2}\right)$$

$$Q_{\lim_{R=177.8cm}} = 1.10\times10^{-6}\ J$$

Appendix 4: Four Scan Transmissions

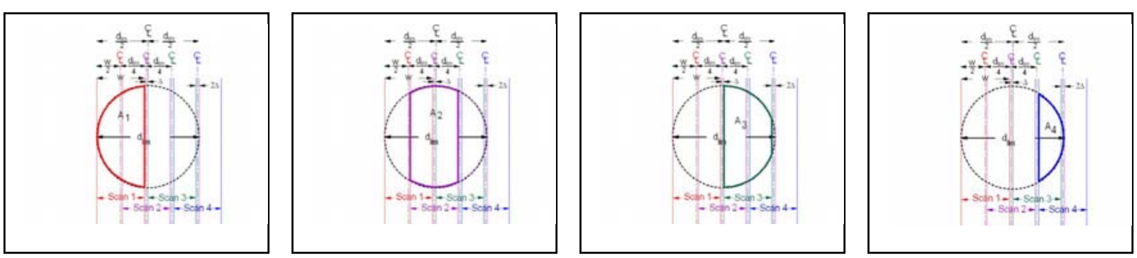


(a) (b)

Figure 38

(a) At the radial distance of 133.4 centimeters from the rotating mirror the diameter of the limiting aperture is divided equally by the four mirror scan centerlines. (b) Aligning the edge of the limiting aperture with edge of the first mirror scans allows for the transmission of four mirror scans (pulse events).

Aligning the edge of the limiting aperture to the same relative edge of the first mirror scan at a radial distance of 133.4 centimeters allows for the transmission of only four principle mirror scans through the limiting aperture. This alignment produces four unequal transmitted areas that yield four unequaled radiant pulse energies transmitted through the limiting aperture.



Area of Scan 1 Area of Scan 2 Area of Scan 3 Area of Scan 4

Figure 39

The figure shows the transmitted areas of each of the four mirror-scans at 133.4 cm radial distance.

First Mirror Scan

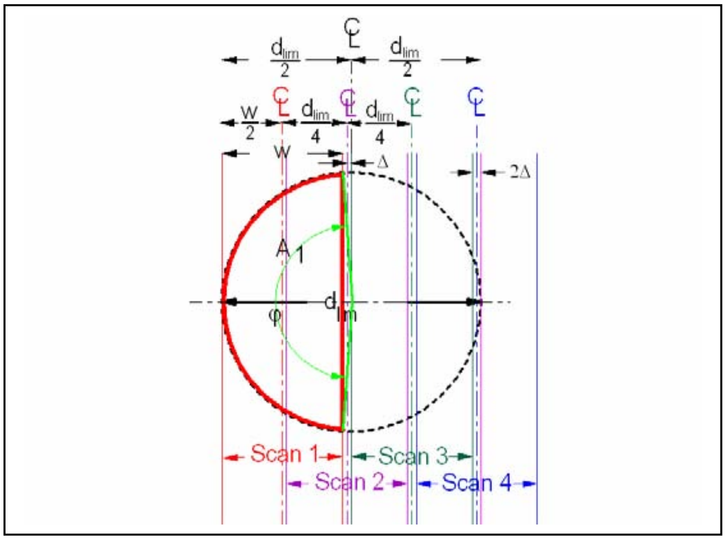


Figure 40

The figure shows the transmitted area of the first mirror scan.

The scan width (w) at a radial distance of 133.4 centimeters can be calculated as follows:

$$w = d_o + \theta(r + R)$$

$$w = 0.25\ cm + \left(0.5 \times 10^{-3}\right) \cdot \left(18\ cm + 133.4\ cm\right)$$

$$w = 0.326\ cm$$

$$\Delta = \left(\frac{d_{\lim}}{2}\right) - \left(\frac{w}{2} + \frac{d_{\lim}}{4}\right)$$

$$\Delta = \left(\frac{0.7\ cm}{2}\right) - \left(\frac{0.326\ cm}{2} + \frac{0.7\ cm}{4}\right)$$

$$\Delta = 0.012\ cm$$

The determination of the wedge half angle for the first transmitted mirror-scan is as follows.

$$\frac{\varphi}{2} = \cos^{-1}\left(\frac{\Delta}{d_{\lim}/2}\right) = \cos^{-1}\left(\frac{2\cdot\Delta}{d_{\lim}}\right)$$

$$\frac{\varphi}{2} = \cos^{-1}\left(\frac{2\cdot(0.012\ cm)}{0.7\ cm}\right)$$

$$\frac{\varphi}{2} = 88.04^{\circ}$$

The determination of the wedge angle for the first transmitted mirror-scan is as follows.

$$\varphi = 2\cdot\left(\frac{\varphi}{2}\right) = 2\cdot(88.04^{\circ})$$

$$\varphi = 176.08^{\circ}$$

The wedge area can be determined to be:

$$A_{\varphi} = A_{\lim}\left(\frac{\varphi}{360^{\circ}}\right)$$

$$A_{\varphi} = (0.385\ cm^2)\cdot\left(\frac{176.08^{\circ}}{360^{\circ}}\right)$$

$$A_{\varphi} = 0.1883\ cm^2$$

The sum of the areas for the two isosceles triangles can be expressed as follows:

$$2\cdot A_{\Delta} = \Delta\cdot\left(\frac{d_{\lim}}{2}\right)\sin\left(\frac{\varphi}{2}\right)$$

$$2 \cdot A_{\Delta} = (0.012\ cm) \cdot \left(\frac{0.7\ cm}{2}\right) \sin\left(\frac{88.04^{\circ}}{2}\right)$$

$$2 \cdot A_{\Delta} = 0.0029\ cm^{2}$$

The transmitted area of the first mirror scan (through the limiting aperture) is the difference between the wedge area and the two triangular areas.

$$A_{\tau} = A_{\varphi} - 2 \cdot A_{\Delta}$$

$$A_{\tau} = 0.1883\ cm^{2} - 0.0029\ cm^{2}$$

$$A_{\tau} = 0.1854\ cm^{2}$$

The transmitted area of the first mirror scan (through the limiting aperture) is approximately equal to half the area of the limiting aperture.

Second Mirror Scan

The transmitted area of the second scan, by inspection, appears to be larger than the other three areas. It is clearly larger than the transmitted areas of the third and fourth mirror scans. The transmitted areas of the third and fourth scans (of the rotating mirror) need not be evaluated since it is clear by inspection that they are the smaller of the set of transmitted areas at this radial distance. Only the larger area is used for the laser hazard analysis. The larger area will yield results with a conservative laser safety bias.

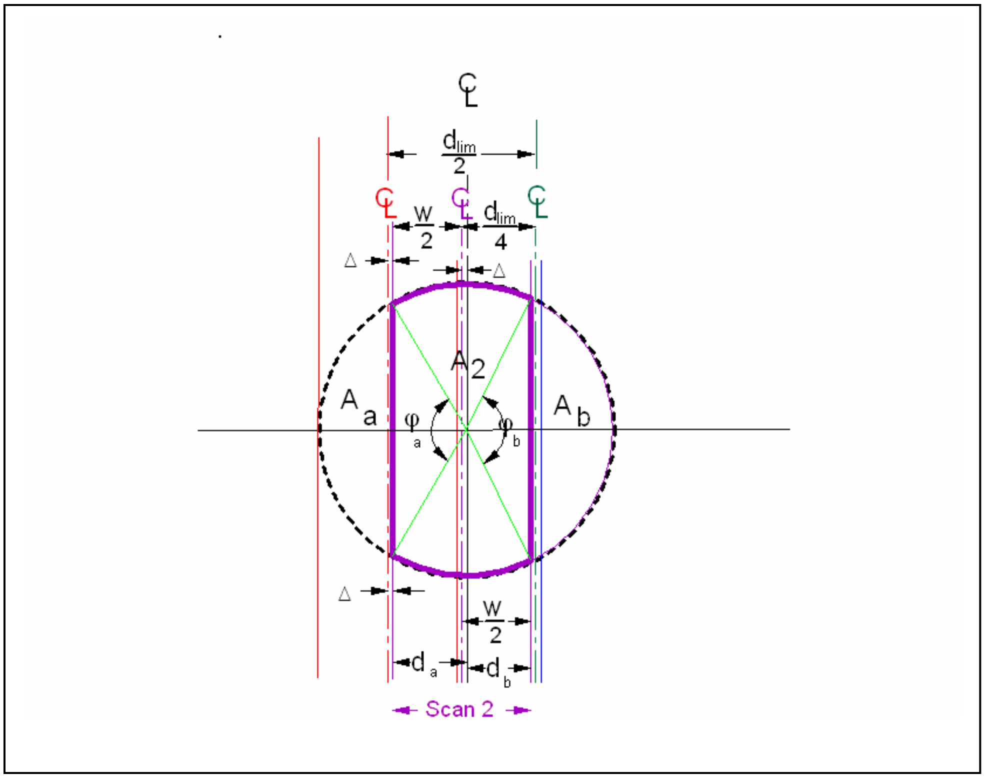


Figure 41

The figure shows the area of the second transmitted scan of the rotating mirror (purple).

Determination of "delta" (Δ) figure 41:

$$\frac{d_{\lim}}{2} = \Delta + \frac{w}{2} + \frac{d_{\lim}}{4}$$

$$\Delta = \left(\frac{d_{\lim}}{2}\right) - \left(\frac{w}{2} + \frac{d_{\lim}}{4}\right)$$

$$\Delta = \left(\frac{0.7\ cm}{2}\right) - \left(\frac{0.326\ cm}{2} + \frac{0.7\ cm}{4}\right)$$

$$\Delta = 0.012\ cm$$

Determination of the "a" dimensions:

$$d_a = \frac{w}{2} + \Delta$$

$$d_a = \frac{0.326\ \ cm}{2} + 0.012\ \ cm$$

$$d_a = 0.175\ \ cm$$

The determination of the "a" side **wedge half angle** for the second transmitted mirror-scan is as follows.

$$\frac{\varphi_a}{2} = \cos^{-1}\left(\frac{d_a}{d_{\lim}/2}\right) = \cos^{-1}\left(\frac{2 \cdot d_a}{d_{\lim}}\right)$$

$$\frac{\varphi_a}{2} = \cos^{-1}\left(\frac{2 \cdot (0.175\ \ cm)}{0.7\ \ cm}\right)$$

$$\frac{\varphi_a}{2} = 60^\circ$$

The determination of the "a" side **wedge angle** for the second transmitted mirror-scan is as follows.

$$\frac{\varphi_a}{2} = 60^\circ$$

$$\varphi_a = 2 \cdot 60^\circ$$

$$\varphi_a = 120^\circ$$

The determination of the “a” wedge area $\left(A_{\varphi_a}\right)$:

$$A_{\varphi_a} = A_{\lim} \cdot \frac{\varphi_a}{360^\circ}$$

$$A_{\varphi_a} = \left(0.385\ cm^2\right) \cdot \frac{120^\circ}{360^\circ}$$

$$A_{\varphi_a} = 0.128\ cm^2$$

The determination of the sum of two “a” triangular areas $\left(A_{\Delta}\right)$:

$$2 \cdot A_{\Delta_a} = \left(d_a\right) \cdot \left(\frac{d_{\lim}}{2}\right) \cdot \sin\left(\frac{\varphi_a}{2}\right)$$

$$2 \cdot A_{\Delta_a} = \left(0.175\ cm\right) \cdot \left(\frac{0.7\ cm}{2}\right) \cdot \sin\left(60^\circ\right)$$

$$2 \cdot A_{\Delta_a} = 0.053\ cm^2$$

The “a” arc chord area $\left(A_a\right)$ can be determined as follows:

$$A_a = A_{\varphi_a} - 2 \cdot A_{\Delta a}$$

$$A_a = 0.128\ cm^2 - 0.053\ cm^2$$

$$A_a = 0.0752\ cm^2$$

Determination of the "b" dimensions:

$$d_b = \frac{w}{2} - \Delta$$

$$d_b = \frac{0.326\ cm}{2} - 0.012\ cm$$

$$d_b = 0.151\ cm$$

The determination of the "b" side **wedge half angle** for the second transmitted mirror-scan is as follows.

$$\frac{\varphi_b}{2} = \cos^{-1}\left(\frac{d_b}{d_{\lim}/2}\right) = \cos^{-1}\left(\frac{2 \cdot d_b}{d_{\lim}}\right)$$

$$\frac{\varphi_b}{2} = \cos^{-1}\left(\frac{2 \cdot (0.151\ cm)}{0.7\ cm}\right)$$

$$\frac{\varphi_b}{2} = 64.50^\circ$$

The determination of the "b" side **wedge angle** for the second transmitted mirror-scan is as follows.

$$\frac{\varphi_b}{2} = 64.50^\circ$$

$$\varphi_b = 2 \cdot (64.50^\circ)$$

$$\varphi_b = 129^\circ$$

The determination of the "b" **wedge area** $\left(A_{\varphi_b}\right)$:

$$A_{\varphi_b} = A_{\lim} \cdot \frac{\varphi_b}{360^\circ}$$

$$A_{\varphi_b} = \left(0.385\ cm^2\right) \cdot \frac{129^\circ}{360^\circ}$$

$$A_{\varphi_b} = 0.138\ cm^2$$

The determination of the sum of two "b" **triangular areas** $\left(A_\Delta\right)$:

$$2 \cdot A_{\Delta_b} = \left(d_b\right) \cdot \left(\frac{d_{\lim}}{2}\right) \cdot \sin\left(\frac{\varphi_b}{2}\right)$$

$$2 \cdot A_{\Delta_b} = \left(0.151\ cm\right) \cdot \left(\frac{0.7\ cm}{2}\right) \cdot \sin\left(64.5^\circ\right)$$

$$2 \cdot A_{\Delta_b} = 0.00476\ cm^2$$

The "b" arc chord area $\left(A_b\right)$ can be determined as follows:

$$A_b = A_{\varphi_b} - 2 \cdot A_{\Delta_b}$$

$$A_b = 0.138\ cm^2 - 0.0476\ cm^2$$

$$A_b = 0.0903\ cm^2$$

The transmitted area $\left(A_\tau\right)$ is:

$$A_\tau = A_{\lim} - \left(A_a + A_b\right)$$

$$A_\tau = 0.385\ cm^2 - \left(0.0752\ cm^2 + 0.0903\ cm^2\right)$$

$$A_\tau = 0.219\ cm^2$$

The scan area at a radial distance of 133.4 centimeters is:

$$A_{scan} = (2 \cdot \pi \cdot R) \cdot w$$

$$A_{scan} = 2 \cdot \pi (133.4\ cm) \cdot 0.326\ cm$$

$$A_{scan} = 272.9\ cm^2$$

The radiant power transmitted through the limiting aperture at a radial distance of 133.4 centimeters is:

$$Q_{\lim} = \frac{\Phi}{\omega} \cdot \frac{A_{\tau}}{A_{scan}}$$

$$Q_{\lim_{133.4cm}} = \left(\frac{7.46 \times 10^{-3} watts}{4\ {rev}/{\sec}} \right) \cdot \left(\frac{0.219\ cm^2 - rev}{272.9\ cm^2} \right)$$

$$Q_{\lim_{133.4cm}} = 1.5 \times 10^{-6} J$$

Excel Spreadsheet Laser Hazard Model (1D Q) for the DeltaSphere-3000
Sample Density = 5 samples/degree & Mirror Rotation Rate = 4 rev/sec

			Laser Hazard Model		for	**DeltaSphere-3000**		**(NIR)**				
Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**		Valid for R <	882	cm			
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**							
Mirror Rotation (ω) =	**4**	**rev / sec**	Rotation time =	0.2500	sec		**NOHD =**	**131.2**	**cm**			
Sampling =	**5**	**sample/degree**	Θ =	3.49E-03	radians							
Limiting Aperture =	0.7	cm	Ω =	1.40E-02	radian/sec		A_{lim}=	0.384845	cm^2			
C_A =	1.445											
Number of Pulses	**R**	**AEL**	**Q_{lim}**	AELx	**T_{lim}**	**t**	**$MPE_{rule\ 1}$**	**Cp**	**$MPE_{rule\ 3}$**	**L**	**α**	α/α_{min}
n	(cm)	(J)	(J)	(J)	(sec)	(sec)	(J/cm^2)		(J/cm^2)	(cm)	(radians)	
1	200.5	1.28E-06	1.04E-06	1.28E-06	0.25	1.39E-04	3.33E-06	1.0000	3.33E-06	218.5	1.14E-03	7.63E-01
2	100.3	1.81E-06	2.07E-06	2.55E-06	0.50	2.78E-04	5.60E-06	0.8409	4.71E-06	118.3	2.11E-03	1.41E+00
3	66.8	2.22E-06	3.11E-06	4.36E-06	0.75	4.17E-04	7.59E-06	0.7598	5.77E-06	84.8	2.95E-03	1.96E+00
4	50.1	2.56E-06	4.14E-06	6.27E-06	1.00	5.56E-04	9.41E-06	0.7071	6.66E-06	68.1	3.67E-03	2.45E+00
5	40.1	2.87E-06	5.18E-06	8.22E-06	1.25	6.94E-04	1.11E-05	0.6687	7.44E-06	58.1	4.30E-03	2.87E+00
6	33.4	3.14E-06	6.22E-06	1.02E-05	1.50	8.33E-04	1.28E-05	0.6389	8.15E-06	51.4	4.86E-03	3.24E+00
7	28.6	3.39E-06	7.25E-06	1.21E-05	1.75	9.72E-04	1.43E-05	0.6148	8.81E-06	46.6	5.36E-03	3.57E+00
8	25.1	3.62E-06	8.29E-06	1.40E-05	2.00	1.11E-03	1.58E-05	0.5946	9.41E-06	43.1	5.80E-03	3.87E+00
9	22.3	3.84E-06	9.33E-06	1.59E-05	2.25	1.25E-03	1.73E-05	0.5774	9.99E-06	40.3	6.21E-03	4.14E+00
10	20.1	4.05E-06	1.04E-05	1.77E-05	2.50	1.39E-03	1.87E-05	0.5623	1.05E-05	38.1	6.57E-03	4.38E+00
11	18.2	4.25E-06	1.14E-05	1.96E-05	2.75	1.53E-03	2.01E-05	0.5491	1.10E-05	36.2	6.90E-03	4.60E+00
12	16.7	4.44E-06	1.24E-05	2.13E-05	3.00	1.67E-03	2.15E-05	0.5373	1.15E-05	34.7	7.20E-03	4.80E+00
13	15.4	4.62E-06	1.35E-05	2.30E-05	3.25	1.81E-03	2.28E-05	0.5266	1.20E-05	33.4	7.48E-03	4.99E+00
14	14.3	4.80E-06	1.45E-05	2.47E-05	3.50	1.94E-03	2.41E-05	0.5170	1.25E-05	32.3	7.73E-03	5.16E+00
15	13.4	4.96E-06	1.55E-05	2.64E-05	3.75	2.08E-03	2.54E-05	0.5081	1.29E-05	31.4	7.97E-03	5.31E+00
16	12.5	5.13E-06	1.66E-05	2.80E-05	4.00	2.22E-03	2.66E-05	0.5000	1.33E-05	30.5	8.19E-03	5.46E+00
17	11.8	5.28E-06	1.76E-05	2.96E-05	4.25	2.36E-03	2.79E-05	0.4925	1.37E-05	29.8	8.39E-03	5.59E+00
18	11.1	5.44E-06	1.87E-05	3.11E-05	4.50	2.50E-03	2.91E-05	0.4855	1.41E-05	29.1	8.58E-03	5.72E+00
19	10.6	5.59E-06	1.97E-05	3.26E-05	4.75	2.64E-03	3.03E-05	0.4790	1.45E-05	28.6	8.76E-03	5.84E+00
20	10.0	5.73E-06	2.07E-05	3.41E-05	5.00	2.78E-03	3.15E-05	0.4729	1.49E-05	28.0	8.92E-03	5.95E+00
21	9.5	5.87E-06	2.18E-05	3.55E-05	5.25	2.92E-03	3.27E-05	0.4671	1.53E-05	27.5	9.07E-03	6.05E+00
22	9.1	6.01E-06	2.28E-05	3.69E-05	5.50	3.06E-03	3.38E-05	0.4617	1.56E-05	27.1	9.22E-03	6.15E+00
23	8.7	6.15E-06	2.38E-05	3.83E-05	5.75	3.19E-03	3.50E-05	0.4566	1.60E-05	26.7	9.36E-03	6.24E+00
24	8.4	6.28E-06	2.49E-05	3.97E-05	6.00	3.33E-03	3.61E-05	0.4518	1.63E-05	26.4	9.49E-03	6.32E+00
25	8.0	6.41E-06	2.59E-05	4.10E-05	6.25	3.47E-03	3.72E-05	0.4472	1.66E-05	26.0	9.61E-03	6.40E+00
26	7.7	6.53E-06	2.69E-05	4.24E-05	6.50	3.61E-03	3.83E-05	0.4429	1.70E-05	25.7	9.72E-03	6.48E+00
27	7.4	6.66E-06	2.80E-05	4.36E-05	6.75	3.75E-03	3.94E-05	0.4387	1.73E-05	25.4	9.83E-03	6.55E+00
28	7.2	6.78E-06	2.90E-05	4.49E-05	7.00	3.89E-03	4.05E-05	0.4347	1.76E-05	25.2	9.94E-03	6.62E+00
29	6.9	6.90E-06	3.00E-05	4.62E-05	7.25	4.03E-03	4.16E-05	0.4309	1.79E-05	24.9	1.00E-02	6.69E+00
30	6.7	7.02E-06	3.11E-05	4.74E-05	7.50	4.17E-03	4.27E-05	0.4273	1.82E-05	24.7	1.01E-02	6.75E+00
31	6.5	7.14E-06	3.21E-05	4.86E-05	7.75	4.31E-03	4.37E-05	0.4238	1.85E-05	24.5	1.02E-02	6.81E+00
32	6.3	7.25E-06	3.32E-05	4.98E-05	8.00	4.44E-03	4.48E-05	0.4204	1.88E-05	24.3	1.03E-02	6.87E+00
33	6.1	7.36E-06	3.42E-05	5.10E-05	8.25	4.58E-03	4.58E-05	0.4172	1.91E-05	24.1	1.04E-02	6.92E+00
34	5.9	7.47E-06	3.52E-05	5.21E-05	8.50	4.72E-03	4.69E-05	0.4141	1.94E-05	23.9	1.05E-02	6.97E+00
35	5.7	7.58E-06	3.63E-05	5.33E-05	8.75	4.86E-03	4.79E-05	0.4111	1.97E-05	23.7	1.05E-02	7.02E+00
36	5.6	7.69E-06	3.73E-05	5.44E-05	9.00	5.00E-03	4.89E-05	0.4082	2.00E-05	23.6	1.06E-02	7.07E+00
37	5.4	7.80E-06	3.83E-05	5.55E-05	9.25	5.14E-03	4.99E-05	0.4055	2.02E-05	23.4	1.07E-02	7.12E+00
39	5.1	8.00E-06	4.04E-05	5.76E-05	9.75	5.42E-03	5.19E-05	0.4002	2.08E-05	23.1	1.08E-02	7.20E+00
40	5.0	8.11E-06	4.14E-05	5.87E-05	10.00	5.56E-03	5.29E-05	0.3976	2.11E-05	23.0	1.09E-02	7.24E+00

Excel Spreadsheet Laser Hazard Model (1D Q) for the DeltaSphere-3000
Sample Density = 5 samples/degree & Mirror Rotation Rate = 8 rev/sec

Laser Hazard Model for **DeltaSphere-3000** **(NIR)**

Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**		Valid for R <	882	cm
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**				
Mirror Rotation (ω) =	**8**	**rev / sec**	Rotation time =	0.1250	sec		**NOHD =**	**92.8**	**cm**
Sampling =	**5**	**sample/degree**	Θ =	3.49E-03	radians				
Limiting Aperture =	0.7	cm	Ω =	2.79E-02	radian/sec		A_{lim}=	0.384845	cm^2
C_A =	1.445								

Number of Pulses n	**R** (cm)	**AEL** (J)	**Q_{lim}** (J)	AELx (J)	**T_{lim}** (sec)	**t** (sec)	**$MPE_{rule\ 1}$** (J/cm^2)	**Cp**	**$MPE_{rule\ 3}$** (J/cm^2)	**L** (cm)	**α** (radians)	α/α_{min}
1	200.5	7.62E-07	5.18E-07	7.62E-07	0.13	6.94E-05	1.98E-06	1.0000	1.98E-06	218.5	1.14E-03	7.63E-01
2	100.3	1.08E-06	1.04E-06	1.52E-06	0.25	1.39E-04	3.33E-06	0.8409	2.80E-06	118.3	2.11E-03	1.41E+00
3	66.8	1.32E-06	1.55E-06	2.59E-06	0.38	2.08E-04	4.51E-06	0.7598	3.43E-06	84.8	2.95E-03	1.96E+00
4	50.1	1.52E-06	2.07E-06	3.73E-06	0.50	2.78E-04	5.60E-06	0.7071	3.96E-06	68.1	3.67E-03	2.45E+00
5	40.1	1.70E-06	2.59E-06	4.89E-06	0.63	3.47E-04	6.62E-06	0.6687	4.43E-06	58.1	4.30E-03	2.87E+00
6	33.4	1.87E-06	3.11E-06	6.05E-06	0.75	4.17E-04	7.59E-06	0.6389	4.85E-06	51.4	4.86E-03	3.24E+00
7	28.6	2.02E-06	3.63E-06	7.20E-06	0.88	4.86E-04	8.52E-06	0.6148	5.24E-06	46.6	5.36E-03	3.57E+00
8	25.1	2.16E-06	4.14E-06	8.34E-06	1.00	5.56E-04	9.41E-06	0.5946	5.60E-06	43.1	5.80E-03	3.87E+00
9	22.3	2.29E-06	4.66E-06	9.46E-06	1.13	6.25E-04	1.03E-05	0.5774	5.94E-06	40.3	6.21E-03	4.14E+00
10	20.1	2.41E-06	5.18E-06	1.06E-05	1.25	6.94E-04	1.11E-05	0.5623	6.26E-06	38.1	6.57E-03	4.38E+00
11	18.2	2.53E-06	5.70E-06	1.16E-05	1.38	7.64E-04	1.20E-05	0.5491	6.56E-06	36.2	6.90E-03	4.60E+00
12	16.7	2.64E-06	6.22E-06	1.27E-05	1.50	8.33E-04	1.28E-05	0.5373	6.86E-06	34.7	7.20E-03	4.80E+00
13	15.4	2.75E-06	6.73E-06	1.37E-05	1.63	9.03E-04	1.36E-05	0.5266	7.14E-06	33.4	7.48E-03	4.99E+00
14	14.3	2.85E-06	7.25E-06	1.47E-05	1.75	9.72E-04	1.43E-05	0.5170	7.41E-06	32.3	7.73E-03	5.16E+00
15	13.4	2.95E-06	7.77E-06	1.57E-05	1.88	1.04E-03	1.51E-05	0.5081	7.67E-06	31.4	7.97E-03	5.31E+00
16	12.5	3.05E-06	8.29E-06	1.66E-05	2.00	1.11E-03	1.58E-05	0.5000	7.92E-06	30.5	8.19E-03	5.46E+00
17	11.8	3.14E-06	8.81E-06	1.76E-05	2.13	1.18E-03	1.66E-05	0.4925	8.16E-06	29.8	8.39E-03	5.59E+00
18	11.1	3.23E-06	9.33E-06	1.85E-05	2.25	1.25E-03	1.73E-05	0.4855	8.40E-06	29.1	8.58E-03	5.72E+00
19	10.6	3.32E-06	9.84E-06	1.94E-05	2.38	1.32E-03	1.80E-05	0.4790	8.63E-06	28.6	8.76E-03	5.84E+00
20	10.0	3.41E-06	1.04E-05	2.03E-05	2.50	1.39E-03	1.87E-05	0.4729	8.85E-06	28.0	8.92E-03	5.95E+00
21	9.5	3.49E-06	1.09E-05	2.11E-05	2.63	1.46E-03	1.94E-05	0.4671	9.07E-06	27.5	9.07E-03	6.05E+00
22	9.1	3.57E-06	1.14E-05	2.20E-05	2.75	1.53E-03	2.01E-05	0.4617	9.28E-06	27.1	9.22E-03	6.15E+00
23	8.7	3.65E-06	1.19E-05	2.28E-05	2.88	1.60E-03	2.08E-05	0.4566	9.49E-06	26.7	9.36E-03	6.24E+00
24	8.4	3.73E-06	1.24E-05	2.36E-05	3.00	1.67E-03	2.15E-05	0.4518	9.70E-06	26.4	9.49E-03	6.32E+00
25	8.0	3.81E-06	1.30E-05	2.44E-05	3.13	1.74E-03	2.21E-05	0.4472	9.90E-06	26.0	9.61E-03	6.40E+00
26	7.7	3.89E-06	1.35E-05	2.52E-05	3.25	1.81E-03	2.28E-05	0.4429	1.01E-05	25.7	9.72E-03	6.48E+00
27	7.4	3.96E-06	1.40E-05	2.60E-05	3.38	1.88E-03	2.34E-05	0.4387	1.03E-05	25.4	9.83E-03	6.55E+00
28	7.2	4.03E-06	1.45E-05	2.67E-05	3.50	1.94E-03	2.41E-05	0.4347	1.05E-05	25.2	9.94E-03	6.62E+00
29	6.9	4.10E-06	1.50E-05	2.75E-05	3.63	2.01E-03	2.47E-05	0.4309	1.07E-05	24.9	1.00E-02	6.69E+00
30	6.7	4.17E-06	1.55E-05	2.82E-05	3.75	2.08E-03	2.54E-05	0.4273	1.08E-05	24.7	1.01E-02	6.75E+00
31	6.5	4.24E-06	1.61E-05	2.89E-05	3.88	2.15E-03	2.60E-05	0.4238	1.10E-05	24.5	1.02E-02	6.81E+00
32	6.3	4.31E-06	1.66E-05	2.96E-05	4.00	2.22E-03	2.66E-05	0.4204	1.12E-05	24.3	1.03E-02	6.87E+00
33	6.1	4.38E-06	1.71E-05	3.03E-05	4.13	2.29E-03	2.73E-05	0.4172	1.14E-05	24.1	1.04E-02	6.92E+00
34	5.9	4.44E-06	1.76E-05	3.10E-05	4.25	2.36E-03	2.79E-05	0.4141	1.15E-05	23.9	1.05E-02	6.97E+00
35	5.7	4.51E-06	1.81E-05	3.17E-05	4.38	2.43E-03	2.85E-05	0.4111	1.17E-05	23.7	1.05E-02	7.02E+00
36	5.6	4.57E-06	1.87E-05	3.23E-05	4.50	2.50E-03	2.91E-05	0.4082	1.19E-05	23.6	1.06E-02	7.07E+00
37	5.4	4.64E-06	1.92E-05	3.30E-05	4.63	2.57E-03	2.97E-05	0.4055	1.20E-05	23.4	1.07E-02	7.12E+00
39	5.1	4.76E-06	2.02E-05	3.43E-05	4.88	2.71E-03	3.09E-05	0.4002	1.24E-05	23.1	1.08E-02	7.20E+00
40	5.0	4.82E-06	2.07E-05	3.49E-05	5.00	2.78E-03	3.15E-05	0.3976	1.25E-05	23.0	1.09E-02	7.24E+00

Excel Spreadsheet Laser Hazard Model (1D Q) for the DeltaSphere-3000
Sample Density = 5 samples/degree & Mirror Rotation Rate = 10 rev/sec

Laser Hazard Model for **DeltaSphere-3000** **(NIR)**

Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**	Valid for R <	882	cm
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**			
Mirror Rotation (ω) =	**10**	**rev / sec**	Rotation time =	0.1000	sec	**NOHD =**	**83.0**	**cm**
Sampling =	**5**	**sample/degree**	Θ =	3.49E-03	radians			
Limiting Aperture =	0.7	cm	Ω =	3.49E-02	radian/sec	A_{lim}=	0.384845	cm^2
C_A =	1.445							

Number of Pulses **n**	**R** (cm)	**AEL** (J)	**Q_{lim}** (J)	AELx (J)	**T_{lim}** (sec)	**t** (sec)	**$MPE_{rule\ 1}$** (J/cm^2)	**Cp**	**$MPE_{rule\ 3}$** (J/cm^2)	**L** (cm)	**α** (radians)	α/α_{min}
1	**200.5**	**6.45E-07**	**4.14E-07**	6.45E-07	0.10	5.56E-05	1.67E-06	1.0000	1.67E-06	218.5	1.14E-03	7.63E-01
2	**100.3**	**9.12E-07**	**8.29E-07**	1.28E-06	0.20	1.11E-04	2.82E-06	0.8409	2.37E-06	118.3	2.11E-03	1.41E+00
3	**66.8**	**1.12E-06**	**1.24E-06**	2.19E-06	0.30	1.67E-04	3.82E-06	0.7598	2.90E-06	84.8	2.95E-03	**1.96E+00**
4	**50.1**	**1.29E-06**	**1.66E-06**	3.15E-06	0.40	2.22E-04	4.74E-06	0.7071	3.35E-06	68.1	3.67E-03	**2.45E+00**
5	**40.1**	**1.44E-06**	**2.07E-06**	4.13E-06	0.50	2.78E-04	5.60E-06	0.6687	3.74E-06	58.1	4.30E-03	**2.87E+00**
6	**33.4**	**1.58E-06**	**2.49E-06**	5.12E-06	0.60	3.33E-04	6.42E-06	0.6389	4.10E-06	51.4	4.86E-03	**3.24E+00**
7	**28.6**	**1.71E-06**	**2.90E-06**	6.09E-06	0.70	3.89E-04	7.21E-06	0.6148	4.43E-06	46.6	5.36E-03	**3.57E+00**
8	**25.1**	**1.82E-06**	**3.32E-06**	7.06E-06	0.80	4.44E-04	7.96E-06	0.5946	4.74E-06	43.1	5.80E-03	**3.87E+00**
9	**22.3**	**1.93E-06**	**3.73E-06**	8.00E-06	0.90	5.00E-04	8.70E-06	0.5774	5.02E-06	40.3	6.21E-03	**4.14E+00**
10	**20.1**	**2.04E-06**	**4.14E-06**	8.93E-06	1.00	5.56E-04	9.41E-06	0.5623	5.29E-06	38.1	6.57E-03	**4.38E+00**
11	**18.2**	**2.14E-06**	**4.56E-06**	9.83E-06	1.10	6.11E-04	1.01E-05	0.5491	5.55E-06	36.2	6.90E-03	**4.60E+00**
12	**16.7**	**2.23E-06**	**4.97E-06**	1.07E-05	1.20	6.67E-04	1.08E-05	0.5373	5.80E-06	34.7	7.20E-03	**4.80E+00**
13	**15.4**	**2.32E-06**	**5.39E-06**	1.16E-05	1.30	7.22E-04	1.15E-05	0.5266	6.04E-06	33.4	7.48E-03	**4.99E+00**
14	**14.3**	**2.41E-06**	**5.80E-06**	1.24E-05	1.40	7.78E-04	1.21E-05	0.5170	6.26E-06	32.3	7.73E-03	**5.16E+00**
15	**13.4**	**2.50E-06**	**6.22E-06**	1.33E-05	1.50	8.33E-04	1.28E-05	0.5081	6.48E-06	31.4	7.97E-03	**5.31E+00**
16	**12.5**	**2.58E-06**	**6.63E-06**	1.41E-05	1.60	8.89E-04	1.34E-05	0.5000	6.70E-06	30.5	8.19E-03	**5.46E+00**
17	**11.8**	**2.66E-06**	**7.05E-06**	1.49E-05	1.70	9.44E-04	1.40E-05	0.4925	6.90E-06	29.8	8.39E-03	**5.59E+00**
18	**11.1**	**2.73E-06**	**7.46E-06**	1.56E-05	1.80	1.00E-03	1.46E-05	0.4855	7.10E-06	29.1	8.58E-03	**5.72E+00**
19	**10.6**	**2.81E-06**	**7.87E-06**	1.64E-05	1.90	1.06E-03	1.52E-05	0.4790	7.30E-06	28.6	8.76E-03	**5.84E+00**
20	**10.0**	**2.88E-06**	**8.29E-06**	1.71E-05	2.00	1.11E-03	1.58E-05	0.4729	7.49E-06	28.0	8.92E-03	**5.95E+00**
21	**9.5**	**2.95E-06**	**8.70E-06**	1.79E-05	2.10	1.17E-03	1.64E-05	0.4671	7.67E-06	27.5	9.07E-03	**6.05E+00**
22	**9.1**	**3.02E-06**	**9.12E-06**	1.86E-05	2.20	1.22E-03	1.70E-05	0.4617	7.85E-06	27.1	9.22E-03	**6.15E+00**
23	**8.7**	**3.09E-06**	**9.53E-06**	1.93E-05	2.30	1.28E-03	1.76E-05	0.4566	8.03E-06	26.7	9.36E-03	**6.24E+00**
24	**8.4**	**3.16E-06**	**9.95E-06**	2.00E-05	2.40	1.33E-03	1.82E-05	0.4518	8.20E-06	26.4	9.49E-03	**6.32E+00**
25	**8.0**	**3.22E-06**	**1.04E-05**	2.06E-05	2.50	1.39E-03	1.87E-05	0.4472	8.37E-06	26.0	9.61E-03	**6.40E+00**
26	**7.7**	**3.29E-06**	**1.08E-05**	2.13E-05	2.60	1.44E-03	1.93E-05	0.4429	8.54E-06	25.7	9.72E-03	**6.48E+00**
27	**7.4**	**3.35E-06**	**1.12E-05**	2.20E-05	2.70	1.50E-03	1.98E-05	0.4387	8.70E-06	25.4	9.83E-03	**6.55E+00**
28	**7.2**	**3.41E-06**	**1.16E-05**	2.26E-05	2.80	1.56E-03	2.04E-05	0.4347	8.86E-06	25.2	9.94E-03	**6.62E+00**
29	**6.9**	**3.47E-06**	**1.20E-05**	2.32E-05	2.90	1.61E-03	2.09E-05	0.4309	9.02E-06	24.9	1.00E-02	**6.69E+00**
30	**6.7**	**3.53E-06**	**1.24E-05**	2.38E-05	3.00	1.67E-03	2.15E-05	0.4273	9.17E-06	24.7	1.01E-02	**6.75E+00**
31	**6.5**	**3.59E-06**	**1.28E-05**	2.44E-05	3.10	1.72E-03	2.20E-05	0.4238	9.32E-06	24.5	1.02E-02	**6.81E+00**
32	**6.3**	**3.65E-06**	**1.33E-05**	2.50E-05	3.20	1.78E-03	2.25E-05	0.4204	9.47E-06	24.3	1.03E-02	**6.87E+00**
33	**6.1**	**3.70E-06**	**1.37E-05**	2.56E-05	3.30	1.83E-03	2.31E-05	0.4172	9.62E-06	24.1	1.04E-02	**6.92E+00**
34	**5.9**	**3.76E-06**	**1.41E-05**	2.62E-05	3.40	1.89E-03	2.36E-05	0.4141	9.76E-06	23.9	1.05E-02	**6.97E+00**
35	**5.7**	**3.81E-06**	**1.45E-05**	2.68E-05	3.50	1.94E-03	2.41E-05	0.4111	9.90E-06	23.7	1.05E-02	**7.02E+00**
36	**5.6**	**3.87E-06**	**1.49E-05**	2.73E-05	3.60	2.00E-03	2.46E-05	0.4082	1.00E-05	23.6	1.06E-02	**7.07E+00**
37	**5.4**	**3.92E-06**	**1.53E-05**	2.79E-05	3.70	2.06E-03	2.51E-05	0.4055	1.02E-05	23.4	1.07E-02	**7.12E+00**
39	**5.1**	**4.03E-06**	**1.62E-05**	2.90E-05	3.90	2.17E-03	2.61E-05	0.4002	1.05E-05	23.1	1.08E-02	**7.20E+00**
40	**5.0**	**4.08E-06**	**1.66E-05**	2.95E-05	4.00	2.22E-03	2.66E-05	0.3976	1.06E-05	23.0	1.09E-02	**7.24E+00**

Excel Spreadsheet Laser Hazard Model (1D Q) for the DeltaSphere-3000
Sample Density = 5 samples/degree & Mirror Rotation Rate = 16 rev/sec

			Laser Hazard Model		for	**DeltaSphere-3000**		**(NIR)**				
Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**		Valid for R <	882	cm			
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**							
Mirror Rotation (ω) =	**16**	**rev / sec**	Rotation time =	0.0625	sec		**NOHD =**	**65.6**	**cm**			
Sampling =	**5**	**sample/degree**	Θ =	3.49E-03	radians							
Limiting Aperture =	0.7	cm	Ω =	5.59E-02	radian/sec		A_{lim}=	0.384845	cm^2			
C_A =	1.445											
Number of Pulses	**R**	**AEL**	**Q_{lim}**	AELx	**T_{lim}**	**t**	**$MPE_{rule\ 1}$**	**Cp**	**$MPE_{rule\ 3}$**	**L**	**α**	α/α_{min}
n	(cm)	(J)	(J)	(J)	(sec)	(sec)	(J/cm^2)		(J/cm^2)	(cm)	(radians)	
1	200.5	4.53E-07	2.59E-07	4.53E-07	0.06	3.47E-05	1.18E-06	1.0000	1.18E-06	218.5	1.14E-03	7.63E-01
2	100.3	6.41E-07	5.18E-07	9.03E-07	0.13	6.94E-05	1.98E-06	0.8409	1.66E-06	118.3	2.11E-03	1.41E+00
3	66.8	7.85E-07	7.77E-07	1.54E-06	0.19	1.04E-04	2.68E-06	0.7598	2.04E-06	84.8	2.95E-03	1.96E+00
4	50.1	9.06E-07	1.04E-06	2.22E-06	0.25	1.39E-04	3.33E-06	0.7071	2.35E-06	68.1	3.67E-03	2.45E+00
5	40.1	1.01E-06	1.30E-06	2.91E-06	0.31	1.74E-04	3.94E-06	0.6687	2.63E-06	58.1	4.30E-03	2.87E+00
6	33.4	1.11E-06	1.55E-06	3.60E-06	0.38	2.08E-04	4.51E-06	0.6389	2.88E-06	51.4	4.86E-03	3.24E+00
7	28.6	1.20E-06	1.81E-06	4.28E-06	0.44	2.43E-04	5.06E-06	0.6148	3.11E-06	46.6	5.36E-03	3.57E+00
8	25.1	1.28E-06	2.07E-06	4.96E-06	0.50	2.78E-04	5.60E-06	0.5946	3.33E-06	43.1	5.80E-03	3.87E+00
9	22.3	1.36E-06	2.33E-06	5.62E-06	0.56	3.13E-04	6.12E-06	0.5774	3.53E-06	40.3	6.21E-03	4.14E+00
10	20.1	1.43E-06	2.59E-06	6.28E-06	0.63	3.47E-04	6.62E-06	0.5623	3.72E-06	38.1	6.57E-03	4.38E+00
11	18.2	1.50E-06	2.85E-06	6.91E-06	0.69	3.82E-04	7.11E-06	0.5491	3.90E-06	36.2	6.90E-03	4.60E+00
12	16.7	1.57E-06	3.11E-06	7.54E-06	0.75	4.17E-04	7.59E-06	0.5373	4.08E-06	34.7	7.20E-03	4.80E+00
13	15.4	1.63E-06	3.37E-06	8.15E-06	0.81	4.51E-04	8.06E-06	0.5266	4.24E-06	33.4	7.48E-03	4.99E+00
14	14.3	1.70E-06	3.63E-06	8.74E-06	0.88	4.86E-04	8.52E-06	0.5170	4.40E-06	32.3	7.73E-03	5.16E+00
15	13.4	1.75E-06	3.89E-06	9.32E-06	0.94	5.21E-04	8.97E-06	0.5081	4.56E-06	31.4	7.97E-03	5.31E+00
16	12.5	1.81E-06	4.14E-06	9.89E-06	1.00	5.56E-04	9.41E-06	0.5000	4.71E-06	30.5	8.19E-03	5.46E+00
17	11.8	1.87E-06	4.40E-06	1.04E-05	1.06	5.90E-04	9.85E-06	0.4925	4.85E-06	29.8	8.39E-03	5.59E+00
18	11.1	1.92E-06	4.66E-06	1.10E-05	1.13	6.25E-04	1.03E-05	0.4855	4.99E-06	29.1	8.58E-03	5.72E+00
19	10.6	1.97E-06	4.92E-06	1.15E-05	1.19	6.60E-04	1.07E-05	0.4790	5.13E-06	28.6	8.76E-03	5.84E+00
20	10.0	2.03E-06	5.18E-06	1.20E-05	1.25	6.94E-04	1.11E-05	0.4729	5.26E-06	28.0	8.92E-03	5.95E+00
21	9.5	2.08E-06	5.44E-06	1.26E-05	1.31	7.29E-04	1.15E-05	0.4671	5.39E-06	27.5	9.07E-03	6.05E+00
22	9.1	2.13E-06	5.70E-06	1.31E-05	1.38	7.64E-04	1.20E-05	0.4617	5.52E-06	27.1	9.22E-03	6.15E+00
23	8.7	2.17E-06	5.96E-06	1.36E-05	1.44	7.99E-04	1.24E-05	0.4566	5.64E-06	26.7	9.36E-03	6.24E+00
24	8.4	2.22E-06	6.22E-06	1.40E-05	1.50	8.33E-04	1.28E-05	0.4518	5.77E-06	26.4	9.49E-03	6.32E+00
25	8.0	2.27E-06	6.48E-06	1.45E-05	1.56	8.68E-04	1.32E-05	0.4472	5.88E-06	26.0	9.61E-03	6.40E+00
26	7.7	2.31E-06	6.73E-06	1.50E-05	1.63	9.03E-04	1.36E-05	0.4429	6.00E-06	25.7	9.72E-03	6.48E+00
27	7.4	2.35E-06	6.99E-06	1.54E-05	1.69	9.38E-04	1.39E-05	0.4387	6.12E-06	25.4	9.83E-03	6.55E+00
28	7.2	2.40E-06	7.25E-06	1.59E-05	1.75	9.72E-04	1.43E-05	0.4347	6.23E-06	25.2	9.94E-03	6.62E+00
29	6.9	2.44E-06	7.51E-06	1.63E-05	1.81	1.01E-03	1.47E-05	0.4309	6.34E-06	24.9	1.00E-02	6.69E+00
30	6.7	2.48E-06	7.77E-06	1.68E-05	1.88	1.04E-03	1.51E-05	0.4273	6.45E-06	24.7	1.01E-02	6.75E+00
31	6.5	2.52E-06	8.03E-06	1.72E-05	1.94	1.08E-03	1.55E-05	0.4238	6.55E-06	24.5	1.02E-02	6.81E+00
32	6.3	2.56E-06	8.29E-06	1.76E-05	2.00	1.11E-03	1.58E-05	0.4204	6.66E-06	24.3	1.03E-02	6.87E+00
33	6.1	2.60E-06	8.55E-06	1.80E-05	2.06	1.15E-03	1.62E-05	0.4172	6.76E-06	24.1	1.04E-02	6.92E+00
34	5.9	2.64E-06	8.81E-06	1.84E-05	2.13	1.18E-03	1.66E-05	0.4141	6.86E-06	23.9	1.05E-02	6.97E+00
35	5.7	2.68E-06	9.07E-06	1.88E-05	2.19	1.22E-03	1.69E-05	0.4111	6.96E-06	23.7	1.05E-02	7.02E+00
36	5.6	2.72E-06	9.33E-06	1.92E-05	2.25	1.25E-03	1.73E-05	0.4082	7.06E-06	23.6	1.06E-02	7.07E+00
37	5.4	2.76E-06	9.58E-06	1.96E-05	2.31	1.28E-03	1.77E-05	0.4055	7.16E-06	23.4	1.07E-02	7.12E+00
39	5.1	2.83E-06	1.01E-05	2.04E-05	2.44	1.35E-03	1.84E-05	0.4002	7.35E-06	23.1	1.08E-02	7.20E+00
40	5.0	2.87E-06	1.04E-05	2.08E-05	2.50	1.39E-03	1.87E-05	0.3976	7.44E-06	23.0	1.09E-02	7.24E+00

Excel Spreadsheet Laser Hazard Model (1D Q) for the DeltaSphere-3000

Sample Density = 6.66 samples/degree & Mirror Rotation Rate = 4 rev/sec

			Laser Hazard Model		for	**DeltaSphere-3000**		**(NIR)**				
Wavelength =	**780**	**nm**	**d_o =**	**0.25**	**cm**		Valid for R <	882	cm			
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**							
Mirror Rotation (ω) =	**4**	**rev / sec**	Rotation time =	0.2500	sec		**NOHD =**	**151.4**	**cm**			
Sampling =	**6.66**	**sample/degree**	Θ =	2.62E-03	radians							
Limiting Aperture =	0.7	cm	Ω =	1.05E-02	radian/sec		A_{lim}=	0.384845	cm^2			
C_A =	1.445											
Number of Pulses	**R**	**AEL**	**Q_{lim}**	AELx	**T_{lim}**	**t**	**$MPE_{rule\ 1}$**	**Cp**	**$MPE_{rule\ 3}$**	**L**	**α**	α/α_{min}
n	(cm)	(J)	(J)	(J)	(sec)	(sec)	(J/cm^2)		(J/cm^2)	(cm)	(radians)	
1	**267.1**	**1.03E-06**	**7.78E-07**	1.03E-06	0.25	1.04E-04	2.68E-06	1.0000	2.68E-06	285.1	8.77E-04	5.85E-01
2	**133.6**	**1.46E-06**	**1.56E-06**	1.61E-06	0.50	2.09E-04	4.52E-06	0.8409	3.80E-06	151.6	1.65E-03	1.10E+00
3	**89.0**	**1.79E-06**	**2.33E-06**	2.79E-06	0.75	3.13E-04	6.12E-06	0.7598	4.65E-06	107.0	2.34E-03	**1.56E+00**
4	**66.8**	**2.07E-06**	**3.11E-06**	4.06E-06	1.00	4.17E-04	7.59E-06	0.7071	5.37E-06	84.8	2.95E-03	**1.97E+00**
5	**53.4**	**2.31E-06**	**3.89E-06**	5.39E-06	1.25	5.21E-04	8.98E-06	0.6687	6.00E-06	71.4	3.50E-03	**2.33E+00**
6	**44.5**	**2.53E-06**	**4.67E-06**	6.75E-06	1.50	6.26E-04	1.03E-05	0.6389	6.58E-06	62.5	4.00E-03	**2.67E+00**
7	**38.2**	**2.73E-06**	**5.45E-06**	8.12E-06	1.75	7.30E-04	1.16E-05	0.6148	7.10E-06	56.2	4.45E-03	**2.97E+00**
8	**33.4**	**2.92E-06**	**6.22E-06**	9.48E-06	2.00	8.34E-04	1.28E-05	0.5946	7.59E-06	51.4	4.86E-03	**3.24E+00**
9	**29.7**	**3.10E-06**	**7.00E-06**	1.08E-05	2.25	9.38E-04	1.40E-05	0.5774	8.05E-06	47.7	5.24E-03	**3.50E+00**
10	**26.7**	**3.27E-06**	**7.78E-06**	1.22E-05	2.50	1.04E-03	1.51E-05	0.5623	8.49E-06	44.7	5.59E-03	**3.73E+00**
11	**24.3**	**3.43E-06**	**8.56E-06**	1.35E-05	2.75	1.15E-03	1.62E-05	0.5491	8.90E-06	42.3	5.91E-03	**3.94E+00**
12	**22.3**	**3.58E-06**	**9.33E-06**	1.48E-05	3.00	1.25E-03	1.73E-05	0.5373	9.30E-06	40.3	6.21E-03	**4.14E+00**
13	**20.5**	**3.73E-06**	**1.01E-05**	1.61E-05	3.25	1.36E-03	1.84E-05	0.5266	9.68E-06	38.5	6.49E-03	**4.32E+00**
14	**19.1**	**3.87E-06**	**1.09E-05**	1.74E-05	3.50	1.46E-03	1.94E-05	0.5170	1.00E-05	37.1	6.74E-03	**4.49E+00**
15	**17.8**	**4.00E-06**	**1.17E-05**	1.86E-05	3.75	1.56E-03	2.05E-05	0.5081	1.04E-05	35.8	6.98E-03	**4.65E+00**
16	**16.7**	**4.13E-06**	**1.24E-05**	1.99E-05	4.00	1.67E-03	2.15E-05	0.5000	1.07E-05	34.7	7.21E-03	**4.80E+00**
17	**15.7**	**4.26E-06**	**1.32E-05**	2.11E-05	4.25	1.77E-03	2.25E-05	0.4925	1.11E-05	33.7	7.42E-03	**4.94E+00**
18	**14.8**	**4.39E-06**	**1.40E-05**	2.23E-05	4.50	1.88E-03	2.35E-05	0.4855	1.14E-05	32.8	7.61E-03	**5.08E+00**
19	**14.1**	**4.51E-06**	**1.48E-05**	2.34E-05	4.75	1.98E-03	2.44E-05	0.4790	1.17E-05	32.1	7.80E-03	**5.20E+00**
20	**13.4**	**4.62E-06**	**1.56E-05**	2.46E-05	5.00	2.09E-03	2.54E-05	0.4729	1.20E-05	31.4	7.97E-03	**5.32E+00**
21	**12.7**	**4.74E-06**	**1.63E-05**	2.57E-05	5.25	2.19E-03	2.63E-05	0.4671	1.23E-05	30.7	8.14E-03	**5.43E+00**
22	**12.1**	**4.85E-06**	**1.71E-05**	2.68E-05	5.50	2.29E-03	2.73E-05	0.4617	1.26E-05	30.1	8.29E-03	**5.53E+00**
23	**11.6**	**4.96E-06**	**1.79E-05**	2.79E-05	5.75	2.40E-03	2.82E-05	0.4566	1.29E-05	29.6	8.44E-03	**5.63E+00**
24	**11.1**	**5.06E-06**	**1.87E-05**	2.90E-05	6.00	2.50E-03	2.91E-05	0.4518	1.32E-05	29.1	8.58E-03	**5.72E+00**
25	**10.7**	**5.17E-06**	**1.94E-05**	3.00E-05	6.25	2.61E-03	3.00E-05	0.4472	1.34E-05	28.7	8.72E-03	**5.81E+00**
26	**10.3**	**5.27E-06**	**2.02E-05**	3.11E-05	6.50	2.71E-03	3.09E-05	0.4429	1.37E-05	28.3	8.84E-03	**5.89E+00**
27	**9.9**	**5.37E-06**	**2.10E-05**	3.21E-05	6.75	2.82E-03	3.18E-05	0.4387	1.40E-05	27.9	8.96E-03	**5.98E+00**
28	**9.5**	**5.47E-06**	**2.18E-05**	3.31E-05	7.00	2.92E-03	3.27E-05	0.4347	1.42E-05	27.5	9.08E-03	**6.05E+00**
29	**9.2**	**5.57E-06**	**2.26E-05**	3.41E-05	7.25	3.02E-03	3.36E-05	0.4309	1.45E-05	27.2	9.19E-03	**6.13E+00**
30	**8.9**	**5.66E-06**	**2.33E-05**	3.51E-05	7.50	3.13E-03	3.44E-05	0.4273	1.47E-05	26.9	9.29E-03	**6.19E+00**
31	**8.6**	**5.75E-06**	**2.41E-05**	3.60E-05	7.75	3.23E-03	3.53E-05	0.4238	1.49E-05	26.6	9.39E-03	**6.26E+00**
32	**8.3**	**5.85E-06**	**2.49E-05**	3.70E-05	8.00	3.34E-03	3.61E-05	0.4204	1.52E-05	26.3	9.49E-03	**6.33E+00**
33	**8.1**	**5.94E-06**	**2.57E-05**	3.79E-05	8.25	3.44E-03	3.70E-05	0.4172	1.54E-05	26.1	9.58E-03	**6.39E+00**
34	**7.9**	**6.03E-06**	**2.64E-05**	3.88E-05	8.50	3.55E-03	3.78E-05	0.4141	1.57E-05	25.9	9.67E-03	**6.45E+00**
35	**7.6**	**6.11E-06**	**2.72E-05**	3.98E-05	8.75	3.65E-03	3.86E-05	0.4111	1.59E-05	25.6	9.75E-03	**6.50E+00**
36	**7.4**	**6.20E-06**	**2.80E-05**	4.07E-05	9.00	3.75E-03	3.95E-05	0.4082	1.61E-05	25.4	9.83E-03	**6.56E+00**
37	**7.2**	**6.29E-06**	**2.88E-05**	4.16E-05	9.25	3.86E-03	4.03E-05	0.4055	1.63E-05	25.2	9.91E-03	**6.61E+00**
39	**6.8**	**6.45E-06**	**3.03E-05**	4.33E-05	9.75	4.07E-03	4.19E-05	0.4002	1.68E-05	24.8	1.01E-02	**6.71E+00**
40	**6.7**	**6.54E-06**	**3.11E-05**	4.41E-05	10.00	4.17E-03	4.27E-05	0.3976	1.70E-05	24.7	1.01E-02	**6.75E+00**

Excel Spreadsheet Laser Hazard Model (1D Q) for the DeltaSphere-3000
Sample Density = 6.66 samples/degree & Mirror Rotation Rate = 8 rev/sec

			Laser Hazard Model		for	**DeltaSphere-3000**		**(NIR)**				
Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**		Valid for R <	882	cm			
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**							
Mirror Rotation (ω) =	**8**	**rev / sec**	Rotation time =	0.1250	sec		**NOHD =**	**107.1**	**cm**			
Sampling =	**6.66**	**sample/degree**	Θ =	2.62E-03	radians							
Limiting Aperture =	0.7	cm	Ω =	2.10E-02	radian/sec		A_{lim}=	0.384845	cm^2			
C_A =	1.445											
Number of Pulses	**R**	**AEL**	**Q_{lim}**	AELx	**T_{lim}**	**t**	**$MPE_{rule\ 1}$**	**Cp**	**$MPE_{rule\ 3}$**	**L**	**α**	α/α_{min}
n	(cm)	(J)	(J)	(J)	(sec)	(sec)	(J/cm^2)		(J/cm^2)	(cm)	(radians)	
1	**267.1**	**6.15E-07**	**3.89E-07**	6.15E-07	0.13	5.21E-05	1.60E-06	1.0000	1.60E-06	285.1	8.77E-04	5.85E-01
2	**133.6**	**8.69E-07**	**7.78E-07**	9.56E-07	0.25	1.04E-04	2.68E-06	0.8409	2.26E-06	151.6	1.65E-03	1.10E+00
3	**89.0**	**1.06E-06**	**1.17E-06**	1.66E-06	0.38	1.56E-04	3.64E-06	0.7598	2.76E-06	107.0	2.34E-03	**1.56E+00**
4	**66.8**	**1.23E-06**	**1.56E-06**	2.42E-06	0.50	2.09E-04	4.52E-06	0.7071	3.19E-06	84.8	2.95E-03	**1.97E+00**
5	**53.4**	**1.37E-06**	**1.94E-06**	3.21E-06	0.63	2.61E-04	5.34E-06	0.6687	3.57E-06	71.4	3.50E-03	**2.33E+00**
6	**44.5**	**1.51E-06**	**2.33E-06**	4.01E-06	0.75	3.13E-04	6.12E-06	0.6389	3.91E-06	62.5	4.00E-03	**2.67E+00**
7	**38.2**	**1.63E-06**	**2.72E-06**	4.83E-06	0.88	3.65E-04	6.87E-06	0.6148	4.22E-06	56.2	4.45E-03	**2.97E+00**
8	**33.4**	**1.74E-06**	**3.11E-06**	5.64E-06	1.00	4.17E-04	7.59E-06	0.5946	4.52E-06	51.4	4.86E-03	**3.24E+00**
9	**29.7**	**1.84E-06**	**3.50E-06**	6.45E-06	1.13	4.69E-04	8.29E-06	0.5774	4.79E-06	47.7	5.24E-03	**3.50E+00**
10	**26.7**	**1.94E-06**	**3.89E-06**	7.24E-06	1.25	5.21E-04	8.98E-06	0.5623	5.05E-06	44.7	5.59E-03	**3.73E+00**
11	**24.3**	**2.04E-06**	**4.28E-06**	8.03E-06	1.38	5.73E-04	9.64E-06	0.5491	5.29E-06	42.3	5.91E-03	**3.94E+00**
12	**22.3**	**2.13E-06**	**4.67E-06**	8.81E-06	1.50	6.26E-04	1.03E-05	0.5373	5.53E-06	40.3	6.21E-03	**4.14E+00**
13	**20.5**	**2.22E-06**	**5.06E-06**	9.58E-06	1.63	6.78E-04	1.09E-05	0.5266	5.76E-06	38.5	6.49E-03	**4.32E+00**
14	**19.1**	**2.30E-06**	**5.45E-06**	1.03E-05	1.75	7.30E-04	1.16E-05	0.5170	5.97E-06	37.1	6.74E-03	**4.49E+00**
15	**17.8**	**2.38E-06**	**5.83E-06**	1.11E-05	1.88	7.82E-04	1.22E-05	0.5081	6.18E-06	35.8	6.98E-03	**4.65E+00**
16	**16.7**	**2.46E-06**	**6.22E-06**	1.18E-05	2.00	8.34E-04	1.28E-05	0.5000	6.39E-06	34.7	7.21E-03	**4.80E+00**
17	**15.7**	**2.53E-06**	**6.61E-06**	1.25E-05	2.13	8.86E-04	1.34E-05	0.4925	6.58E-06	33.7	7.42E-03	**4.94E+00**
18	**14.8**	**2.61E-06**	**7.00E-06**	1.32E-05	2.25	9.38E-04	1.40E-05	0.4855	6.77E-06	32.8	7.61E-03	**5.08E+00**
19	**14.1**	**2.68E-06**	**7.39E-06**	1.39E-05	2.38	9.91E-04	1.45E-05	0.4790	6.96E-06	32.1	7.80E-03	**5.20E+00**
20	**13.4**	**2.75E-06**	**7.78E-06**	1.46E-05	2.50	1.04E-03	1.51E-05	0.4729	7.14E-06	31.4	7.97E-03	**5.32E+00**
21	**12.7**	**2.82E-06**	**8.17E-06**	1.53E-05	2.63	1.09E-03	1.57E-05	0.4671	7.32E-06	30.7	8.14E-03	**5.43E+00**
22	**12.1**	**2.88E-06**	**8.56E-06**	1.59E-05	2.75	1.15E-03	1.62E-05	0.4617	7.49E-06	30.1	8.29E-03	**5.53E+00**
23	**11.6**	**2.95E-06**	**8.95E-06**	1.66E-05	2.88	1.20E-03	1.68E-05	0.4566	7.66E-06	29.6	8.44E-03	**5.63E+00**
24	**11.1**	**3.01E-06**	**9.33E-06**	1.72E-05	3.00	1.25E-03	1.73E-05	0.4518	7.82E-06	29.1	8.58E-03	**5.72E+00**
25	**10.7**	**3.07E-06**	**9.72E-06**	1.79E-05	3.13	1.30E-03	1.78E-05	0.4472	7.98E-06	28.7	8.72E-03	**5.81E+00**
26	**10.3**	**3.13E-06**	**1.01E-05**	1.85E-05	3.25	1.36E-03	1.84E-05	0.4429	8.14E-06	28.3	8.84E-03	**5.89E+00**
27	**9.9**	**3.19E-06**	**1.05E-05**	1.91E-05	3.38	1.41E-03	1.89E-05	0.4387	8.29E-06	27.9	8.96E-03	**5.98E+00**
28	**9.5**	**3.25E-06**	**1.09E-05**	1.97E-05	3.50	1.46E-03	1.94E-05	0.4347	8.45E-06	27.5	9.08E-03	**6.05E+00**
29	**9.2**	**3.31E-06**	**1.13E-05**	2.03E-05	3.63	1.51E-03	1.99E-05	0.4309	8.60E-06	27.2	9.19E-03	**6.13E+00**
30	**8.9**	**3.37E-06**	**1.17E-05**	2.09E-05	3.75	1.56E-03	2.05E-05	0.4273	8.74E-06	26.9	9.29E-03	**6.19E+00**
31	**8.6**	**3.42E-06**	**1.21E-05**	2.14E-05	3.88	1.62E-03	2.10E-05	0.4238	8.89E-06	26.6	9.39E-03	**6.26E+00**
32	**8.3**	**3.48E-06**	**1.24E-05**	2.20E-05	4.00	1.67E-03	2.15E-05	0.4204	9.03E-06	26.3	9.49E-03	**6.33E+00**
33	**8.1**	**3.53E-06**	**1.28E-05**	2.25E-05	4.13	1.72E-03	2.20E-05	0.4172	9.17E-06	26.1	9.58E-03	**6.39E+00**
34	**7.9**	**3.58E-06**	**1.32E-05**	2.31E-05	4.25	1.77E-03	2.25E-05	0.4141	9.31E-06	25.9	9.67E-03	**6.45E+00**
35	**7.6**	**3.64E-06**	**1.36E-05**	2.36E-05	4.38	1.82E-03	2.30E-05	0.4111	9.44E-06	25.6	9.75E-03	**6.50E+00**
36	**7.4**	**3.69E-06**	**1.40E-05**	2.42E-05	4.50	1.88E-03	2.35E-05	0.4082	9.58E-06	25.4	9.83E-03	**6.56E+00**
37	**7.2**	**3.74E-06**	**1.44E-05**	2.47E-05	4.63	1.93E-03	2.39E-05	0.4055	9.71E-06	25.2	9.91E-03	**6.61E+00**
39	**6.8**	**3.84E-06**	**1.52E-05**	2.57E-05	4.88	2.03E-03	2.49E-05	0.4002	9.97E-06	24.8	1.01E-02	**6.71E+00**
40	**6.7**	**3.89E-06**	**1.56E-05**	2.63E-05	5.00	2.09E-03	2.54E-05	0.3976	1.01E-05	24.7	1.01E-02	**6.75E+00**

Excel Spreadsheet Laser Hazard Model (1D Q) for the DeltaSphere-3000
Sample Density = 6.66 samples/degree, Mirror Rotation Rate = 10 rev/sec

Laser Hazard Model for **DeltaSphere-3000** **(NIR)**

Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**	Valid for R <	882	cm
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**			
Mirror Rotation (ω) =	**10**	**rev / sec**	Rotation time =	0.1000	sec	**NOHD =**	**95.8**	**cm**
Sampling =	**6.66**	**sample/degree**	Θ =	2.62E-03	radians			
Limiting Aperture =	0.7	cm	Ω =	2.62E-02	radian/sec	A_{lim}=	0.384845	cm^2
C_A =	1.445							

Number of Pulses n	**R** (cm)	**AEL** (J)	**Q_{lim}** (J)	AELx (J)	**T_{lim}** (sec)	**t** (sec)	**$MPE_{rule\ 1}$** (J/cm^2)	**Cp**	**$MPE_{rule\ 3}$** (J/cm^2)	**L** (cm)	**α** (radians)	α/α_{min}
1	**267.1**	**5.20E-07**	**3.11E-07**	5.20E-07	0.10	4.17E-05	1.35E-06	1.0000	1.35E-06	285.1	8.77E-04	5.85E-01
2	**133.6**	**7.35E-07**	**6.22E-07**	8.09E-07	0.20	8.34E-05	2.27E-06	0.8409	1.91E-06	151.6	1.65E-03	1.10E+00
3	**89.0**	**9.00E-07**	**9.33E-07**	1.40E-06	0.30	1.25E-04	3.08E-06	0.7598	2.34E-06	107.0	2.34E-03	**1.56E+00**
4	**66.8**	**1.04E-06**	**1.24E-06**	2.04E-06	0.40	1.67E-04	3.82E-06	0.7071	2.70E-06	84.8	2.95E-03	**1.97E+00**
5	**53.4**	**1.16E-06**	**1.56E-06**	2.71E-06	0.50	2.09E-04	4.52E-06	0.6687	3.02E-06	71.4	3.50E-03	**2.33E+00**
6	**44.5**	**1.27E-06**	**1.87E-06**	3.39E-06	0.60	2.50E-04	5.18E-06	0.6389	3.31E-06	62.5	4.00E-03	**2.67E+00**
7	**38.2**	**1.38E-06**	**2.18E-06**	4.08E-06	0.70	2.92E-04	5.81E-06	0.6148	3.57E-06	56.2	4.45E-03	**2.97E+00**
8	**33.4**	**1.47E-06**	**2.49E-06**	4.77E-06	0.80	3.34E-04	6.42E-06	0.5946	3.82E-06	51.4	4.86E-03	**3.24E+00**
9	**29.7**	**1.56E-06**	**2.80E-06**	5.45E-06	0.90	3.75E-04	7.02E-06	0.5774	4.05E-06	47.7	5.24E-03	**3.50E+00**
10	**26.7**	**1.64E-06**	**3.11E-06**	6.13E-06	1.00	4.17E-04	7.59E-06	0.5623	4.27E-06	44.7	5.59E-03	**3.73E+00**
11	**24.3**	**1.72E-06**	**3.42E-06**	6.80E-06	1.10	4.59E-04	8.16E-06	0.5491	4.48E-06	42.3	5.91E-03	**3.94E+00**
12	**22.3**	**1.80E-06**	**3.73E-06**	7.46E-06	1.20	5.01E-04	8.71E-06	0.5373	4.68E-06	40.3	6.21E-03	**4.14E+00**
13	**20.5**	**1.87E-06**	**4.04E-06**	8.10E-06	1.30	5.42E-04	9.24E-06	0.5266	4.87E-06	38.5	6.49E-03	**4.32E+00**
14	**19.1**	**1.95E-06**	**4.36E-06**	8.74E-06	1.40	5.84E-04	9.77E-06	0.5170	5.05E-06	37.1	6.74E-03	**4.49E+00**
15	**17.8**	**2.01E-06**	**4.67E-06**	9.37E-06	1.50	6.26E-04	1.03E-05	0.5081	5.23E-06	35.8	6.98E-03	**4.65E+00**
16	**16.7**	**2.08E-06**	**4.98E-06**	9.99E-06	1.60	6.67E-04	1.08E-05	0.5000	5.40E-06	34.7	7.21E-03	**4.80E+00**
17	**15.7**	**2.14E-06**	**5.29E-06**	1.06E-05	1.70	7.09E-04	1.13E-05	0.4925	5.57E-06	33.7	7.42E-03	**4.94E+00**
18	**14.8**	**2.21E-06**	**5.60E-06**	1.12E-05	1.80	7.51E-04	1.18E-05	0.4855	5.73E-06	32.8	7.61E-03	**5.08E+00**
19	**14.1**	**2.27E-06**	**5.91E-06**	1.18E-05	1.90	7.92E-04	1.23E-05	0.4790	5.89E-06	32.1	7.80E-03	**5.20E+00**
20	**13.4**	**2.32E-06**	**6.22E-06**	1.24E-05	2.00	8.34E-04	1.28E-05	0.4729	6.04E-06	31.4	7.97E-03	**5.32E+00**
21	**12.7**	**2.38E-06**	**6.53E-06**	1.29E-05	2.10	8.76E-04	1.32E-05	0.4671	6.19E-06	30.7	8.14E-03	**5.43E+00**
22	**12.1**	**2.44E-06**	**6.85E-06**	1.35E-05	2.20	9.18E-04	1.37E-05	0.4617	6.33E-06	30.1	8.29E-03	**5.53E+00**
23	**11.6**	**2.49E-06**	**7.16E-06**	1.40E-05	2.30	9.59E-04	1.42E-05	0.4566	6.48E-06	29.6	8.44E-03	**5.63E+00**
24	**11.1**	**2.55E-06**	**7.47E-06**	1.46E-05	2.40	1.00E-03	1.46E-05	0.4518	6.62E-06	29.1	8.58E-03	**5.72E+00**
25	**10.7**	**2.60E-06**	**7.78E-06**	1.51E-05	2.50	1.04E-03	1.51E-05	0.4472	6.75E-06	28.7	8.72E-03	**5.81E+00**
26	**10.3**	**2.65E-06**	**8.09E-06**	1.56E-05	2.60	1.08E-03	1.55E-05	0.4429	6.89E-06	28.3	8.84E-03	**5.89E+00**
27	**9.9**	**2.70E-06**	**8.40E-06**	1.61E-05	2.70	1.13E-03	1.60E-05	0.4387	7.02E-06	27.9	8.96E-03	**5.98E+00**
28	**9.5**	**2.75E-06**	**8.71E-06**	1.66E-05	2.80	1.17E-03	1.64E-05	0.4347	7.15E-06	27.5	9.08E-03	**6.05E+00**
29	**9.2**	**2.80E-06**	**9.02E-06**	1.71E-05	2.90	1.21E-03	1.69E-05	0.4309	7.27E-06	27.2	9.19E-03	**6.13E+00**
30	**8.9**	**2.85E-06**	**9.33E-06**	1.76E-05	3.00	1.25E-03	1.73E-05	0.4273	7.40E-06	26.9	9.29E-03	**6.19E+00**
31	**8.6**	**2.89E-06**	**9.65E-06**	1.81E-05	3.10	1.29E-03	1.77E-05	0.4238	7.52E-06	26.6	9.39E-03	**6.26E+00**
32	**8.3**	**2.94E-06**	**9.96E-06**	1.86E-05	3.20	1.33E-03	1.82E-05	0.4204	7.64E-06	26.3	9.49E-03	**6.33E+00**
33	**8.1**	**2.99E-06**	**1.03E-05**	1.91E-05	3.30	1.38E-03	1.86E-05	0.4172	7.76E-06	26.1	9.58E-03	**6.39E+00**
34	**7.9**	**3.03E-06**	**1.06E-05**	1.95E-05	3.40	1.42E-03	1.90E-05	0.4141	7.87E-06	25.9	9.67E-03	**6.45E+00**
35	**7.6**	**3.08E-06**	**1.09E-05**	2.00E-05	3.50	1.46E-03	1.94E-05	0.4111	7.99E-06	25.6	9.75E-03	**6.50E+00**
36	**7.4**	**3.12E-06**	**1.12E-05**	2.05E-05	3.60	1.50E-03	1.98E-05	0.4082	8.10E-06	25.4	9.83E-03	**6.56E+00**
37	**7.2**	**3.16E-06**	**1.15E-05**	2.09E-05	3.70	1.54E-03	2.03E-05	0.4055	8.21E-06	25.2	9.91E-03	**6.61E+00**
39	**6.8**	**3.25E-06**	**1.21E-05**	2.18E-05	3.90	1.63E-03	2.11E-05	0.4002	8.43E-06	24.8	1.01E-02	**6.71E+00**
40	**6.7**	**3.29E-06**	**1.24E-05**	2.22E-05	4.00	1.67E-03	2.15E-05	0.3976	8.54E-06	24.7	1.01E-02	**6.75E+00**

Appendix 5

Excel Spreadsheet Laser Hazard Model (1D Q) for the DeltaSphere-3000
Sample Density = 10 samples/degree & Mirror Rotation Rate = 4 rev/sec

Laser Hazard Model for **DeltaSphere-3000** **(NIR)**

Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**	Valid for R <	882 cm
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**		
Mirror Rotation (ω) =	**4**	**rev / sec**	Rotation time =	0.2500	sec	**NOHD =**	**185.5 cm**
Sampling =	**10**	**sample/degree**	Θ =	1.75E-03	radians		
Limiting Aperture =	0.7	cm	Ω =	6.98E-03	radian/sec	A_{lim}=	0.384845 cm^2
C_A =	1.445						

Number of Pulses n	R (cm)	AEL (J)	Q_{lim} (J)	AELx (J)	T_{lim} (sec)	t (sec)	$MPE_{rule\ 1}$ (J/cm^2)	Cp	$MPE_{rule\ 3}$ (J/cm^2)	L (cm)	α (radians)	α/α_{min}
1	401.1	7.62E-07	5.18E-07	7.62E-07	0.25	6.94E-05	1.98E-06	1.0000	1.98E-06	419.1	5.97E-04	3.98E-01
2	200.5	1.08E-06	1.04E-06	1.08E-06	0.50	1.39E-04	3.33E-06	0.8409	2.80E-06	218.5	1.14E-03	7.63E-01
3	133.7	1.32E-06	1.55E-06	1.45E-06	0.75	2.08E-04	4.51E-06	0.7598	3.43E-06	151.7	1.65E-03	1.10E+00
4	100.3	1.52E-06	2.07E-06	2.15E-06	1.00	2.78E-04	5.60E-06	0.7071	3.96E-06	118.3	2.11E-03	1.41E+00
5	80.2	1.70E-06	2.59E-06	2.89E-06	1.25	3.47E-04	6.62E-06	0.6687	4.43E-06	98.2	2.55E-03	1.70E+00
6	66.8	1.87E-06	3.11E-06	3.67E-06	1.50	4.17E-04	7.59E-06	0.6389	4.85E-06	84.8	2.95E-03	1.96E+00
7	57.3	2.02E-06	3.63E-06	4.46E-06	1.75	4.86E-04	8.52E-06	0.6148	5.24E-06	75.3	3.32E-03	2.21E+00
8	50.1	2.16E-06	4.14E-06	5.27E-06	2.00	5.56E-04	9.41E-06	0.5946	5.60E-06	68.1	3.67E-03	2.45E+00
9	44.6	2.29E-06	4.66E-06	6.09E-06	2.25	6.25E-04	1.03E-05	0.5774	5.94E-06	62.6	4.00E-03	2.66E+00
10	40.1	2.41E-06	5.18E-06	6.91E-06	2.50	6.94E-04	1.11E-05	0.5623	6.26E-06	58.1	4.30E-03	2.87E+00
11	36.5	2.53E-06	5.70E-06	7.73E-06	2.75	7.64E-04	1.20E-05	0.5491	6.56E-06	54.5	4.59E-03	3.06E+00
12	33.4	2.64E-06	6.22E-06	8.56E-06	3.00	8.33E-04	1.28E-05	0.5373	6.86E-06	51.4	4.86E-03	3.24E+00
13	30.9	2.75E-06	6.73E-06	9.37E-06	3.25	9.03E-04	1.36E-05	0.5266	7.14E-06	48.9	5.12E-03	3.41E+00
14	28.6	2.85E-06	7.25E-06	1.02E-05	3.50	9.72E-04	1.43E-05	0.5170	7.41E-06	46.6	5.36E-03	3.57E+00
15	26.7	2.95E-06	7.77E-06	1.10E-05	3.75	1.04E-03	1.51E-05	0.5081	7.67E-06	44.7	5.59E-03	3.73E+00
16	25.1	3.05E-06	8.29E-06	1.18E-05	4.00	1.11E-03	1.58E-05	0.5000	7.92E-06	43.1	5.80E-03	3.87E+00
17	23.6	3.14E-06	8.81E-06	1.26E-05	4.25	1.18E-03	1.66E-05	0.4925	8.16E-06	41.6	6.01E-03	4.01E+00
18	22.3	3.23E-06	9.33E-06	1.34E-05	4.50	1.25E-03	1.73E-05	0.4855	8.40E-06	40.3	6.21E-03	4.14E+00
19	21.1	3.32E-06	9.84E-06	1.42E-05	4.75	1.32E-03	1.80E-05	0.4790	8.63E-06	39.1	6.39E-03	4.26E+00
20	20.1	3.41E-06	1.04E-05	1.49E-05	5.00	1.39E-03	1.87E-05	0.4729	8.85E-06	38.1	6.57E-03	4.38E+00
21	19.1	3.49E-06	1.09E-05	1.57E-05	5.25	1.46E-03	1.94E-05	0.4671	9.07E-06	37.1	6.74E-03	4.49E+00
22	18.2	3.57E-06	1.14E-05	1.64E-05	5.50	1.53E-03	2.01E-05	0.4617	9.28E-06	36.2	6.90E-03	4.60E+00
23	17.4	3.65E-06	1.19E-05	1.72E-05	5.75	1.60E-03	2.08E-05	0.4566	9.49E-06	35.4	7.05E-03	4.70E+00
24	16.7	3.73E-06	1.24E-05	1.79E-05	6.00	1.67E-03	2.15E-05	0.4518	9.70E-06	34.7	7.20E-03	4.80E+00
25	16.0	3.81E-06	1.30E-05	1.87E-05	6.25	1.74E-03	2.21E-05	0.4472	9.90E-06	34.0	7.34E-03	4.90E+00
26	15.4	3.89E-06	1.35E-05	1.94E-05	6.50	1.81E-03	2.28E-05	0.4429	1.01E-05	33.4	7.48E-03	4.99E+00
27	14.9	3.96E-06	1.40E-05	2.01E-05	6.75	1.88E-03	2.34E-05	0.4387	1.03E-05	32.9	7.61E-03	5.07E+00
28	14.3	4.03E-06	1.45E-05	2.08E-05	7.00	1.94E-03	2.41E-05	0.4347	1.05E-05	32.3	7.73E-03	5.16E+00
29	13.8	4.10E-06	1.50E-05	2.15E-05	7.25	2.01E-03	2.47E-05	0.4309	1.07E-05	31.8	7.85E-03	5.24E+00
30	13.4	4.17E-06	1.55E-05	2.22E-05	7.50	2.08E-03	2.54E-05	0.4273	1.08E-05	31.4	7.97E-03	5.31E+00
31	12.9	4.24E-06	1.61E-05	2.29E-05	7.75	2.15E-03	2.60E-05	0.4238	1.10E-05	30.9	8.08E-03	5.39E+00
32	12.5	4.31E-06	1.66E-05	2.35E-05	8.00	2.22E-03	2.66E-05	0.4204	1.12E-05	30.5	8.19E-03	5.46E+00
33	12.2	4.38E-06	1.71E-05	2.42E-05	8.25	2.29E-03	2.73E-05	0.4172	1.14E-05	30.2	8.29E-03	5.53E+00
34	11.8	4.44E-06	1.76E-05	2.49E-05	8.50	2.36E-03	2.79E-05	0.4141	1.15E-05	29.8	8.39E-03	5.59E+00
35	11.5	4.51E-06	1.81E-05	2.55E-05	8.75	2.43E-03	2.85E-05	0.4111	1.17E-05	29.5	8.49E-03	5.66E+00
36	11.1	4.57E-06	1.87E-05	2.61E-05	9.00	2.50E-03	2.91E-05	0.4082	1.19E-05	29.1	8.58E-03	5.72E+00
37	10.8	4.64E-06	1.92E-05	2.68E-05	9.25	2.57E-03	2.97E-05	0.4055	1.20E-05	28.8	8.67E-03	5.78E+00
39	10.3	4.76E-06	2.02E-05	2.80E-05	9.75	2.71E-03	3.09E-05	0.4002	1.24E-05	28.3	8.84E-03	5.89E+00
40	10.0	4.82E-06	2.07E-05	2.87E-05	10.00	2.78E-03	3.15E-05	0.3976	1.25E-05	28.0	8.92E-03	5.95E+00

Excel Spreadsheet Laser Hazard Model (1D Q) for the DeltaSphere-3000
Sample Density = 10 samples/degree & Mirror Rotation Rate = 8 rev/sec

			Laser Hazard Model		for	**DeltaSphere-3000**		**(NIR)**	
Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**		Valid for R <	882	cm
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**				
Mirror Rotation (ω) =	**8**	**rev / sec**	Rotation time =	0.1250	sec		**NOHD =**	**131.2**	**cm**
Sampling =	**10**	**sample/degree**	Θ =	1.75E-03	radians				
Limiting Aperture =	0.7	cm	Ω =	1.40E-02	radian/sec		A_{lim}=	0.384845	cm^2
C_A =	1.445								

Number of Pulses	**R**	**AEL**	**Q_{lim}**	AELx	**T_{lim}**	**t**	**$MPE_{rule\ 1}$**	**Cp**	**$MPE_{rule\ 3}$**	**L**	**α**	α/α_{min}
n	(cm)	(J)	(J)	(J)	(sec)	(sec)	(J/cm^2)		(J/cm^2)	(cm)	(radians)	
1	**401.1**	**4.53E-07**	**2.59E-07**	4.53E-07	0.13	3.47E-05	1.18E-06	1.0000	1.18E-06	419.1	5.97E-04	3.98E-01
2	**200.5**	**6.41E-07**	**5.18E-07**	6.41E-07	0.25	6.94E-05	1.98E-06	0.8409	1.66E-06	218.5	1.14E-03	7.63E-01
3	**133.7**	**7.85E-07**	**7.77E-07**	8.62E-07	0.38	1.04E-04	2.68E-06	0.7598	2.04E-06	151.7	1.65E-03	**1.10E+00**
4	**100.3**	**9.06E-07**	**1.04E-06**	1.28E-06	0.50	1.39E-04	3.33E-06	0.7071	2.35E-06	118.3	2.11E-03	**1.41E+00**
5	**80.2**	**1.01E-06**	**1.30E-06**	1.72E-06	0.63	1.74E-04	3.94E-06	0.6687	2.63E-06	98.2	2.55E-03	**1.70E+00**
6	**66.8**	**1.11E-06**	**1.55E-06**	2.18E-06	0.75	2.08E-04	4.51E-06	0.6389	2.88E-06	84.8	2.95E-03	**1.96E+00**
7	**57.3**	**1.20E-06**	**1.81E-06**	2.65E-06	0.88	2.43E-04	5.06E-06	0.6148	3.11E-06	75.3	3.32E-03	**2.21E+00**
8	**50.1**	**1.28E-06**	**2.07E-06**	3.13E-06	1.00	2.78E-04	5.60E-06	0.5946	3.33E-06	68.1	3.67E-03	**2.45E+00**
9	**44.6**	**1.36E-06**	**2.33E-06**	3.62E-06	1.13	3.13E-04	6.12E-06	0.5774	3.53E-06	62.6	4.00E-03	**2.66E+00**
10	**40.1**	**1.43E-06**	**2.59E-06**	4.11E-06	1.25	3.47E-04	6.62E-06	0.5623	3.72E-06	58.1	4.30E-03	**2.87E+00**
11	**36.5**	**1.50E-06**	**2.85E-06**	4.60E-06	1.38	3.82E-04	7.11E-06	0.5491	3.90E-06	54.5	4.59E-03	**3.06E+00**
12	**33.4**	**1.57E-06**	**3.11E-06**	5.09E-06	1.50	4.17E-04	7.59E-06	0.5373	4.08E-06	51.4	4.86E-03	**3.24E+00**
13	**30.9**	**1.63E-06**	**3.37E-06**	5.57E-06	1.63	4.51E-04	8.06E-06	0.5266	4.24E-06	48.9	5.12E-03	**3.41E+00**
14	**28.6**	**1.70E-06**	**3.63E-06**	6.06E-06	1.75	4.86E-04	8.52E-06	0.5170	4.40E-06	46.6	5.36E-03	**3.57E+00**
15	**26.7**	**1.75E-06**	**3.89E-06**	6.54E-06	1.88	5.21E-04	8.97E-06	0.5081	4.56E-06	44.7	5.59E-03	**3.73E+00**
16	**25.1**	**1.81E-06**	**4.14E-06**	7.01E-06	2.00	5.56E-04	9.41E-06	0.5000	4.71E-06	43.1	5.80E-03	**3.87E+00**
17	**23.6**	**1.87E-06**	**4.40E-06**	7.49E-06	2.13	5.90E-04	9.85E-06	0.4925	4.85E-06	41.6	6.01E-03	**4.01E+00**
18	**22.3**	**1.92E-06**	**4.66E-06**	7.95E-06	2.25	6.25E-04	1.03E-05	0.4855	4.99E-06	40.3	6.21E-03	**4.14E+00**
19	**21.1**	**1.97E-06**	**4.92E-06**	8.42E-06	2.38	6.60E-04	1.07E-05	0.4790	5.13E-06	39.1	6.39E-03	**4.26E+00**
20	**20.1**	**2.03E-06**	**5.18E-06**	8.87E-06	2.50	6.94E-04	1.11E-05	0.4729	5.26E-06	38.1	6.57E-03	**4.38E+00**
21	**19.1**	**2.08E-06**	**5.44E-06**	9.33E-06	2.63	7.29E-04	1.15E-05	0.4671	5.39E-06	37.1	6.74E-03	**4.49E+00**
22	**18.2**	**2.13E-06**	**5.70E-06**	9.78E-06	2.75	7.64E-04	1.20E-05	0.4617	5.52E-06	36.2	6.90E-03	**4.60E+00**
23	**17.4**	**2.17E-06**	**5.96E-06**	1.02E-05	2.88	7.99E-04	1.24E-05	0.4566	5.64E-06	35.4	7.05E-03	**4.70E+00**
24	**16.7**	**2.22E-06**	**6.22E-06**	1.07E-05	3.00	8.33E-04	1.28E-05	0.4518	5.77E-06	34.7	7.20E-03	**4.80E+00**
25	**16.0**	**2.27E-06**	**6.48E-06**	1.11E-05	3.13	8.68E-04	1.32E-05	0.4472	5.88E-06	34.0	7.34E-03	**4.90E+00**
26	**15.4**	**2.31E-06**	**6.73E-06**	1.15E-05	3.25	9.03E-04	1.36E-05	0.4429	6.00E-06	33.4	7.48E-03	**4.99E+00**
27	**14.9**	**2.35E-06**	**6.99E-06**	1.19E-05	3.38	9.38E-04	1.39E-05	0.4387	6.12E-06	32.9	7.61E-03	**5.07E+00**
28	**14.3**	**2.40E-06**	**7.25E-06**	1.24E-05	3.50	9.72E-04	1.43E-05	0.4347	6.23E-06	32.3	7.73E-03	**5.16E+00**
29	**13.8**	**2.44E-06**	**7.51E-06**	1.28E-05	3.63	1.01E-03	1.47E-05	0.4309	6.34E-06	31.8	7.85E-03	**5.24E+00**
30	**13.4**	**2.48E-06**	**7.77E-06**	1.32E-05	3.75	1.04E-03	1.51E-05	0.4273	6.45E-06	31.4	7.97E-03	**5.31E+00**
31	**12.9**	**2.52E-06**	**8.03E-06**	1.36E-05	3.88	1.08E-03	1.55E-05	0.4238	6.55E-06	30.9	8.08E-03	**5.39E+00**
32	**12.5**	**2.56E-06**	**8.29E-06**	1.40E-05	4.00	1.11E-03	1.58E-05	0.4204	6.66E-06	30.5	8.19E-03	**5.46E+00**
33	**12.2**	**2.60E-06**	**8.55E-06**	1.44E-05	4.13	1.15E-03	1.62E-05	0.4172	6.76E-06	30.2	8.29E-03	**5.53E+00**
34	**11.8**	**2.64E-06**	**8.81E-06**	1.48E-05	4.25	1.18E-03	1.66E-05	0.4141	6.86E-06	29.8	8.39E-03	**5.59E+00**
35	**11.5**	**2.68E-06**	**9.07E-06**	1.52E-05	4.38	1.22E-03	1.69E-05	0.4111	6.96E-06	29.5	8.49E-03	**5.66E+00**
36	**11.1**	**2.72E-06**	**9.33E-06**	1.55E-05	4.50	1.25E-03	1.73E-05	0.4082	7.06E-06	29.1	8.58E-03	**5.72E+00**
37	**10.8**	**2.76E-06**	**9.58E-06**	1.59E-05	4.63	1.28E-03	1.77E-05	0.4055	7.16E-06	28.8	8.67E-03	**5.78E+00**
39	**10.3**	**2.83E-06**	**1.01E-05**	1.67E-05	4.88	1.35E-03	1.84E-05	0.4002	7.35E-06	28.3	8.84E-03	**5.89E+00**
40	**10.0**	**2.87E-06**	**1.04E-05**	1.70E-05	5.00	1.39E-03	1.87E-05	0.3976	7.44E-06	28.0	8.92E-03	**5.95E+00**

Appendix 5

Excel Spreadsheet Laser Hazard Model (1D Q) for the DeltaSphere-3000

Sample Density = 13.3 samples/degree & Mirror Rotation Rate = 4 rev/sec

			Laser Hazard Model		for	**DeltaSphere-3000**		**(NIR)**
Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**	Valid for R <	882	cm
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**			
Mirror Rotation (ω) =	**4**	**rev / sec**	Rotation time =	0.2500	sec	**NOHD =**	**214.0**	**cm**
Sampling =	**13.3**	**sample/degree**	Θ =	1.31E-03	radians			
Limiting Aperture =	0.7	cm	Ω =	5.25E-03	radian/sec	A_{lim}=	0.384845	cm^2
C_A =	1.445							

Number of Pulses n	R (cm)	AEL (J)	Q_{lim} (J)	AELx (J)	T_{lim} (sec)	t (sec)	$MPE_{rule\ 1}$ (J/cm^2)	Cp	$MPE_{rule\ 3}$ (J/cm^2)	L (cm)	α (radians)	α/α_{min}
1	**533.4**	**6.15E-07**	**3.90E-07**	6.15E-07	0.25	5.22E-05	1.60E-06	1.0000	1.60E-06	551.4	4.53E-04	3.02E-01
2	**266.7**	**8.70E-07**	**7.79E-07**	8.70E-07	0.50	1.04E-04	2.69E-06	0.8409	2.26E-06	284.7	8.78E-04	5.85E-01
3	**177.8**	**1.07E-06**	**1.17E-06**	1.07E-06	0.75	1.57E-04	3.64E-06	0.7598	2.77E-06	195.8	1.28E-03	**8.51E-01**
4	**133.4**	**1.23E-06**	**1.56E-06**	1.36E-06	1.00	2.09E-04	4.52E-06	0.7071	3.20E-06	151.4	1.65E-03	**1.10E+00**
5	**106.7**	**1.38E-06**	**1.95E-06**	1.84E-06	1.25	2.61E-04	5.34E-06	0.6687	3.57E-06	124.7	2.01E-03	**1.34E+00**
6	**88.9**	**1.51E-06**	**2.34E-06**	2.35E-06	1.50	3.13E-04	6.13E-06	0.6389	3.91E-06	106.9	2.34E-03	**1.56E+00**
7	**76.2**	**1.63E-06**	**2.73E-06**	2.88E-06	1.75	3.65E-04	6.88E-06	0.6148	4.23E-06	94.2	2.65E-03	**1.77E+00**
8	**66.7**	**1.74E-06**	**3.12E-06**	3.43E-06	2.00	4.18E-04	7.60E-06	0.5946	4.52E-06	84.7	2.95E-03	**1.97E+00**
9	**59.3**	**1.85E-06**	**3.51E-06**	3.98E-06	2.25	4.70E-04	8.30E-06	0.5774	4.79E-06	77.3	3.24E-03	**2.16E+00**
10	**53.3**	**1.95E-06**	**3.90E-06**	4.55E-06	2.50	5.22E-04	8.99E-06	0.5623	5.05E-06	71.3	3.50E-03	**2.34E+00**
11	**48.5**	**2.04E-06**	**4.28E-06**	5.11E-06	2.75	5.74E-04	9.65E-06	0.5491	5.30E-06	66.5	3.76E-03	**2.51E+00**
12	**44.5**	**2.13E-06**	**4.67E-06**	5.69E-06	3.00	6.27E-04	1.03E-05	0.5373	5.54E-06	62.5	4.00E-03	**2.67E+00**
13	**41.0**	**2.22E-06**	**5.06E-06**	6.26E-06	3.25	6.79E-04	1.09E-05	0.5266	5.76E-06	59.0	4.23E-03	**2.82E+00**
14	**38.1**	**2.30E-06**	**5.45E-06**	6.84E-06	3.50	7.31E-04	1.16E-05	0.5170	5.98E-06	56.1	4.46E-03	**2.97E+00**
15	**35.6**	**2.38E-06**	**5.84E-06**	7.42E-06	3.75	7.83E-04	1.22E-05	0.5081	6.19E-06	53.6	4.67E-03	**3.11E+00**
16	**33.3**	**2.46E-06**	**6.23E-06**	7.99E-06	4.00	8.35E-04	1.28E-05	0.5000	6.39E-06	51.3	4.87E-03	**3.25E+00**
17	**31.4**	**2.54E-06**	**6.62E-06**	8.56E-06	4.25	8.88E-04	1.34E-05	0.4925	6.59E-06	49.4	5.06E-03	**3.38E+00**
18	**29.6**	**2.61E-06**	**7.01E-06**	9.13E-06	4.50	9.40E-04	1.40E-05	0.4855	6.78E-06	47.6	5.25E-03	**3.50E+00**
19	**28.1**	**2.68E-06**	**7.40E-06**	9.70E-06	4.75	9.92E-04	1.45E-05	0.4790	6.97E-06	46.1	5.43E-03	**3.62E+00**
20	**26.7**	**2.75E-06**	**7.79E-06**	1.03E-05	5.00	1.04E-03	1.51E-05	0.4729	7.15E-06	44.7	5.60E-03	**3.73E+00**
21	**25.4**	**2.82E-06**	**8.18E-06**	1.08E-05	5.25	1.10E-03	1.57E-05	0.4671	7.32E-06	43.4	5.76E-03	**3.84E+00**
22	**24.2**	**2.89E-06**	**8.57E-06**	1.14E-05	5.50	1.15E-03	1.62E-05	0.4617	7.50E-06	42.2	5.92E-03	**3.95E+00**
23	**23.2**	**2.95E-06**	**8.96E-06**	1.19E-05	5.75	1.20E-03	1.68E-05	0.4566	7.66E-06	41.2	6.07E-03	**4.05E+00**
24	**22.2**	**3.01E-06**	**9.35E-06**	1.25E-05	6.00	1.25E-03	1.73E-05	0.4518	7.83E-06	40.2	6.21E-03	**4.14E+00**
25	**21.3**	**3.08E-06**	**9.74E-06**	1.30E-05	6.25	1.31E-03	1.79E-05	0.4472	7.99E-06	39.3	6.36E-03	**4.24E+00**
26	**20.5**	**3.14E-06**	**1.01E-05**	1.36E-05	6.50	1.36E-03	1.84E-05	0.4429	8.15E-06	38.5	6.49E-03	**4.33E+00**
27	**19.8**	**3.20E-06**	**1.05E-05**	1.41E-05	6.75	1.41E-03	1.89E-05	0.4387	8.30E-06	37.8	6.62E-03	**4.41E+00**
28	**19.1**	**3.26E-06**	**1.09E-05**	1.46E-05	7.00	1.46E-03	1.95E-05	0.4347	8.46E-06	37.1	6.75E-03	**4.50E+00**
29	**18.4**	**3.31E-06**	**1.13E-05**	1.52E-05	7.25	1.51E-03	2.00E-05	0.4309	8.61E-06	36.4	6.87E-03	**4.58E+00**
30	**17.8**	**3.37E-06**	**1.17E-05**	1.57E-05	7.50	1.57E-03	2.05E-05	0.4273	8.75E-06	35.8	6.99E-03	**4.66E+00**
31	**17.2**	**3.43E-06**	**1.21E-05**	1.62E-05	7.75	1.62E-03	2.10E-05	0.4238	8.90E-06	35.2	7.10E-03	**4.73E+00**
32	**16.7**	**3.48E-06**	**1.25E-05**	1.67E-05	8.00	1.67E-03	2.15E-05	0.4204	9.04E-06	34.7	7.21E-03	**4.81E+00**
33	**16.2**	**3.53E-06**	**1.29E-05**	1.72E-05	8.25	1.72E-03	2.20E-05	0.4172	9.18E-06	34.2	7.32E-03	**4.88E+00**
34	**15.7**	**3.59E-06**	**1.32E-05**	1.77E-05	8.50	1.78E-03	2.25E-05	0.4141	9.32E-06	33.7	7.42E-03	**4.95E+00**
35	**15.2**	**3.64E-06**	**1.36E-05**	1.83E-05	8.75	1.83E-03	2.30E-05	0.4111	9.45E-06	33.2	7.52E-03	**5.01E+00**
36	**14.8**	**3.69E-06**	**1.40E-05**	1.87E-05	9.00	1.88E-03	2.35E-05	0.4082	9.59E-06	32.8	7.62E-03	**5.08E+00**
37	**14.4**	**3.74E-06**	**1.44E-05**	1.92E-05	9.25	1.93E-03	2.40E-05	0.4055	9.72E-06	32.4	7.71E-03	**5.14E+00**
39	**13.7**	**3.84E-06**	**1.52E-05**	2.02E-05	9.75	2.04E-03	2.49E-05	0.4002	9.98E-06	31.7	7.89E-03	**5.26E+00**
40	**13.3**	**3.89E-06**	**1.56E-05**	2.07E-05	10.00	2.09E-03	2.54E-05	0.3976	1.01E-05	31.3	7.98E-03	**5.32E+00**

Excel Spreadsheet Laser Hazard Model (1D Q) for the DeltaSphere-3000
Sample Density = 20 samples/degree & Mirror Rotation Rate = 4 rev/sec

			Laser Hazard Model		for	**DeltaSphere-3000**		**(NIR)**	
Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**		Valid for R <	882	cm
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**				
Mirror Rotation (ω) =	**4**	**rev / sec**	Rotation time =	0.2500	sec		**NOHD =**	**262.4**	**cm**
Sampling =	**20**	**sample/degree**	Θ =	8.73E-04	radians				
Limiting Aperture =	0.7	cm	Ω =	3.49E-03	radian/sec		A_{lim}=	0.384845	cm^2
C_A =	1.445								

Number of Pulses n	**R** (cm)	**AEL** (J)	**Q_{lim}** (J)	AELx (J)	**T_{lim}** (sec)	**t** (sec)	**$MPE_{rule\ 1}$** (J/cm^2)	**Cp**	**$MPE_{rule\ 3}$** (J/cm^2)	**L** (cm)	**α** (radians)	α/α_{min}
1	**802.1**	**4.53E-07**	**2.59E-07**	4.53E-07	0.25	3.47E-05	1.18E-06	1.0000	1.18E-06	820.1	3.05E-04	2.03E-01
2	**401.1**	**6.41E-07**	**5.18E-07**	6.41E-07	0.50	6.94E-05	1.98E-06	0.8409	1.66E-06	419.1	5.97E-04	3.98E-01
3	**267.4**	**7.85E-07**	**7.77E-07**	7.85E-07	0.75	1.04E-04	2.68E-06	0.7598	2.04E-06	285.4	8.76E-04	**5.84E-01**
4	**200.5**	**9.06E-07**	**1.04E-06**	9.06E-07	1.00	1.39E-04	3.33E-06	0.7071	2.35E-06	218.5	1.14E-03	**7.63E-01**
5	**160.4**	**1.01E-06**	**1.30E-06**	1.01E-06	1.25	1.74E-04	3.94E-06	0.6687	2.63E-06	178.4	1.40E-03	**9.34E-01**
6	**133.7**	**1.11E-06**	**1.55E-06**	1.22E-06	1.50	2.08E-04	4.51E-06	0.6389	2.88E-06	151.7	1.65E-03	**1.10E+00**
7	**114.6**	**1.20E-06**	**1.81E-06**	1.51E-06	1.75	2.43E-04	5.06E-06	0.6148	3.11E-06	132.6	1.89E-03	**1.26E+00**
8	**100.3**	**1.28E-06**	**2.07E-06**	1.81E-06	2.00	2.78E-04	5.60E-06	0.5946	3.33E-06	118.3	2.11E-03	**1.41E+00**
9	**89.1**	**1.36E-06**	**2.33E-06**	2.11E-06	2.25	3.13E-04	6.12E-06	0.5774	3.53E-06	107.1	2.33E-03	**1.56E+00**
10	**80.2**	**1.43E-06**	**2.59E-06**	2.43E-06	2.50	3.47E-04	6.62E-06	0.5623	3.72E-06	98.2	2.55E-03	**1.70E+00**
11	**72.9**	**1.50E-06**	**2.85E-06**	2.75E-06	2.75	3.82E-04	7.11E-06	0.5491	3.90E-06	90.9	2.75E-03	**1.83E+00**
12	**66.8**	**1.57E-06**	**3.11E-06**	3.08E-06	3.00	4.17E-04	7.59E-06	0.5373	4.08E-06	84.8	2.95E-03	**1.96E+00**
13	**61.7**	**1.63E-06**	**3.37E-06**	3.42E-06	3.25	4.51E-04	8.06E-06	0.5266	4.24E-06	79.7	3.14E-03	**2.09E+00**
14	**57.3**	**1.70E-06**	**3.63E-06**	3.75E-06	3.50	4.86E-04	8.52E-06	0.5170	4.40E-06	75.3	3.32E-03	**2.21E+00**
15	**53.5**	**1.75E-06**	**3.89E-06**	4.09E-06	3.75	5.21E-04	8.97E-06	0.5081	4.56E-06	71.5	3.50E-03	**2.33E+00**
16	**50.1**	**1.81E-06**	**4.14E-06**	4.43E-06	4.00	5.56E-04	9.41E-06	0.5000	4.71E-06	68.1	3.67E-03	**2.45E+00**
17	**47.2**	**1.87E-06**	**4.40E-06**	4.78E-06	4.25	5.90E-04	9.85E-06	0.4925	4.85E-06	65.2	3.84E-03	**2.56E+00**
18	**44.6**	**1.92E-06**	**4.66E-06**	5.12E-06	4.50	6.25E-04	1.03E-05	0.4855	4.99E-06	62.6	4.00E-03	**2.66E+00**
19	**42.2**	**1.97E-06**	**4.92E-06**	5.47E-06	4.75	6.60E-04	1.07E-05	0.4790	5.13E-06	60.2	4.15E-03	**2.77E+00**
20	**40.1**	**2.03E-06**	**5.18E-06**	5.81E-06	5.00	6.94E-04	1.11E-05	0.4729	5.26E-06	58.1	4.30E-03	**2.87E+00**
21	**38.2**	**2.08E-06**	**5.44E-06**	6.16E-06	5.25	7.29E-04	1.15E-05	0.4671	5.39E-06	56.2	4.45E-03	**2.97E+00**
22	**36.5**	**2.13E-06**	**5.70E-06**	6.50E-06	5.50	7.64E-04	1.20E-05	0.4617	5.52E-06	54.5	4.59E-03	**3.06E+00**
23	**34.9**	**2.17E-06**	**5.96E-06**	6.85E-06	5.75	7.99E-04	1.24E-05	0.4566	5.64E-06	52.9	4.73E-03	**3.15E+00**
24	**33.4**	**2.22E-06**	**6.22E-06**	7.19E-06	6.00	8.33E-04	1.28E-05	0.4518	5.77E-06	51.4	4.86E-03	**3.24E+00**
25	**32.1**	**2.27E-06**	**6.48E-06**	7.54E-06	6.25	8.68E-04	1.32E-05	0.4472	5.88E-06	50.1	4.99E-03	**3.33E+00**
26	**30.9**	**2.31E-06**	**6.73E-06**	7.88E-06	6.50	9.03E-04	1.36E-05	0.4429	6.00E-06	48.9	5.12E-03	**3.41E+00**
27	**29.7**	**2.35E-06**	**6.99E-06**	8.22E-06	6.75	9.38E-04	1.39E-05	0.4387	6.12E-06	47.7	5.24E-03	**3.49E+00**
28	**28.6**	**2.40E-06**	**7.25E-06**	8.57E-06	7.00	9.72E-04	1.43E-05	0.4347	6.23E-06	46.6	5.36E-03	**3.57E+00**
29	**27.7**	**2.44E-06**	**7.51E-06**	8.91E-06	7.25	1.01E-03	1.47E-05	0.4309	6.34E-06	45.7	5.48E-03	**3.65E+00**
30	**26.7**	**2.48E-06**	**7.77E-06**	9.25E-06	7.50	1.04E-03	1.51E-05	0.4273	6.45E-06	44.7	5.59E-03	**3.73E+00**
31	**25.9**	**2.52E-06**	**8.03E-06**	9.58E-06	7.75	1.08E-03	1.55E-05	0.4238	6.55E-06	43.9	5.70E-03	**3.80E+00**
32	**25.1**	**2.56E-06**	**8.29E-06**	9.92E-06	8.00	1.11E-03	1.58E-05	0.4204	6.66E-06	43.1	5.80E-03	**3.87E+00**
33	**24.3**	**2.60E-06**	**8.55E-06**	1.03E-05	8.25	1.15E-03	1.62E-05	0.4172	6.76E-06	42.3	5.91E-03	**3.94E+00**
34	**23.6**	**2.64E-06**	**8.81E-06**	1.06E-05	8.50	1.18E-03	1.66E-05	0.4141	6.86E-06	41.6	6.01E-03	**4.01E+00**
35	**22.9**	**2.68E-06**	**9.07E-06**	1.09E-05	8.75	1.22E-03	1.69E-05	0.4111	6.96E-06	40.9	6.11E-03	**4.07E+00**
36	**22.3**	**2.72E-06**	**9.33E-06**	1.12E-05	9.00	1.25E-03	1.73E-05	0.4082	7.06E-06	40.3	6.21E-03	**4.14E+00**
37	**21.7**	**2.76E-06**	**9.58E-06**	1.16E-05	9.25	1.28E-03	1.77E-05	0.4055	7.16E-06	39.7	6.30E-03	**4.20E+00**
39	**20.6**	**2.83E-06**	**1.01E-05**	1.22E-05	9.75	1.35E-03	1.84E-05	0.4002	7.35E-06	38.6	6.48E-03	**4.32E+00**
40	**20.1**	**2.87E-06**	**1.04E-05**	1.26E-05	10.00	1.39E-03	1.87E-05	0.3976	7.44E-06	38.1	6.57E-03	**4.38E+00**

Excel Spreadsheet Laser Hazard Model (2D Q) for the DeltaSphere-3000

Mirror Rotation Rate = 4 rev/sec (Spreadsheet page 1)

			Laser Hazard Model		for	**DeltaSphere-3000**		**(NIR)**				
			r =	**18**	cm							
Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**		Valid for R <	882	cm			
Power =	**7.46**	**mw**	**θ =**	**0.5**	**milliradians**							
Mirror Rotation (ω) =	**4**	**rev / sec**	Rotation time =	0.2500	sec							
Sampling =	**13.3**	**sample/degree**	Θ =	1.31E-03	radians		A_{lim} =	0.38485				
Limiting Aperture =	0.7	cm	Ω =	5.25E-03	radian/sec							
C_A =	1.445											
Number of Pulses	**R**	**AEL**	**Q_{lim}**	AELx	**T_{lim}**	**t**	**$MPE_{rule\ 1}$**	**Cp**	**$MPE_{rule\ 3}$**	**L**	**α**	α/α_{min}
n	(cm)	(J)	(J)	(J)	(sec)	(sec)	(J/cm^2)		(J/cm^2)	(cm)	(radians)	
	882	**4.220E-07**	1.850E-07	4.22E-07		3.16E-05	1.10E-06	1.0000	1.10E-06	900.0	2.78E-04	1.85E-01
	700	**5.018E-07**	**2.532E-07**	5.02E-07		3.98E-05	1.30E-06	1.0000	1.30E-06	718.0	3.48E-04	2.32E-01
1	**533.4**	**6.153E-07**	**3.489E-07**	6.15E-07	0.25	5.22E-05	1.60E-06	1.0000	1.60E-06	551.4	4.53E-04	3.02E-01
2	**266.7**	**8.701E-07**	**6.297E-07**	8.70E-07	0.50	1.04E-04	2.69E-06	0.8409	2.26E-06	284.7	8.78E-04	5.85E-01
3	**177.8**	**1.066E-06**	**1.100E-06**	1.07E-06	0.75	1.57E-04	3.64E-06	0.7598	2.77E-06	195.8	1.28E-03	**8.51E-01**
4	**133.4**	**1.231E-06**	**1.499E-06**	1.36E-06	1.00	2.09E-04	4.52E-06	0.7071	3.20E-06	151.4	1.65E-03	**1.10E+00**

Appendix 7

Excel Spreadsheet Laser Hazard Model (1D Q):
DeltaSphere-3000 Modified Configuration (τ=0.8)
Mirror Rotation Rate = **4 rev/sec @ 13.3 samples /degree**

Laser Hazard Model for **DeltaSphere-3000** **(NIR)**

Wavelength =	**780**	**nm**	d_{o} =	**0.25**	**cm**		Valid for R <	882	cm
Power =	**5.97**	**mw**	θ =	**0.5**	**milliradians**				
Mirror Rotation (ω) =	**8**	**rev / sec**	Rotation time =	0.1250	sec		**NOHD = 84.0**	**cm**	
Sampling =	**10**	**sample/degree**	Θ =	1.75E-03		radians			
Limiting Aperture =	0.7	cm	Ω =	1.40E-02		radian/sec	A_{lim}=	0.3848451	cm^2
C_A =	1.445								

Number of Pulses n	**R** (cm)	**AEL** (J)	**Q_{lim}** (J)	AELx (J)	**T_{lim}** (sec)	**t** (sec)	**$MPE_{rule 1}$Cp** (J/cm^2)	**$MPE_{rule 3}$** (J/cm^2)	**L** (cm)	**α** (radians)	α/α_{min}
1	**401.1**	**4.53E-07**	**2.07E-07**	4.53E-07		0.13	3.47E-05	1.18E-06	1.0000	1.18E-06	419.1
2	**200.5**	**6.41E-07**	**4.15E-07**	6.41E-07		0.25	6.94E-05	1.98E-06	0.8409	1.66E-06	218.5
3	**133.7**	**7.85E-07**	**6.22E-07**	8.62E-07		0.38	1.04E-04	2.68E-06	0.7598	2.04E-06	151.7
4	**100.3**	**9.06E-07**	**8.29E-07**	1.28E-06		0.50	1.39E-04	3.33E-06	0.7071	2.35E-06	118.3
5	**80.2**	**1.01E-06**	**1.04E-06**	1.72E-06		0.63	1.74E-04	3.94E-06	0.6687	2.63E-06	98.2
6	**66.8**	**1.11E-06**	**1.24E-06**	2.18E-06		0.75	2.08E-04	4.51E-06	0.6389	2.88E-06	84.8
7	**57.3**	**1.20E-06**	**1.45E-06**	2.65E-06		0.88	2.43E-04	5.06E-06	0.6148	3.11E-06	75.3
8	**50.1**	**1.28E-06**	**1.66E-06**	3.13E-06		1.00	2.78E-04	5.60E-06	0.5946	3.33E-06	68.1
9	**44.6**	**1.36E-06**	**1.87E-06**	3.62E-06		1.13	3.13E-04	6.12E-06	0.5774	3.53E-06	62.6
10	**40.1**	**1.43E-06**	**2.07E-06**	4.11E-06		1.25	3.47E-04	6.62E-06	0.5623	3.72E-06	58.1
11	**36.5**	**1.50E-06**	**2.28E-06**	4.60E-06		1.38	3.82E-04	7.11E-06	0.5491	3.90E-06	54.5
12	**33.4**	**1.57E-06**	**2.49E-06**	5.09E-06		1.50	4.17E-04	7.59E-06	0.5373	4.08E-06	51.4
13	**30.9**	**1.63E-06**	**2.69E-06**	5.57E-06		1.63	4.51E-04	8.06E-06	0.5266	4.24E-06	48.9
14	**28.6**	**1.70E-06**	**2.90E-06**	6.06E-06		1.75	4.86E-04	8.52E-06	0.5170	4.40E-06	46.6
15	**26.7**	**1.75E-06**	**3.11E-06**	6.54E-06		1.88	5.21E-04	8.97E-06	0.5081	4.56E-06	44.7
16	**25.1**	**1.81E-06**	**3.32E-06**	7.01E-06		2.00	5.56E-04	9.41E-06	0.5000	4.71E-06	43.1
17	**23.6**	**1.87E-06**	**3.52E-06**	7.49E-06		2.13	5.90E-04	9.85E-06	0.4925	4.85E-06	41.6
18	**22.3**	**1.92E-06**	**3.73E-06**	7.95E-06		2.25	6.25E-04	1.03E-05	0.4855	4.99E-06	40.3
19	**21.1**	**1.97E-06**	**3.94E-06**	8.42E-06		2.38	6.60E-04	1.07E-05	0.4790	5.13E-06	39.1
20	**20.1**	**2.03E-06**	**4.15E-06**	8.87E-06		2.50	6.94E-04	1.11E-05	0.4729	5.26E-06	38.1
21	**19.1**	**2.08E-06**	**4.35E-06**	9.33E-06		2.63	7.29E-04	1.15E-05	0.4671	5.39E-06	37.1
22	**18.2**	**2.13E-06**	**4.56E-06**	9.78E-06		2.75	7.64E-04	1.20E-05	0.4617	5.52E-06	36.2
23	**17.4**	**2.17E-06**	**4.77E-06**	1.02E-05		2.88	7.99E-04	1.24E-05	0.4566	5.64E-06	35.4
24	**16.7**	**2.22E-06**	**4.98E-06**	1.07E-05		3.00	8.33E-04	1.28E-05	0.4518	5.77E-06	34.7
25	**16.0**	**2.27E-06**	**5.18E-06**	1.11E-05		3.13	8.68E-04	1.32E-05	0.4472	5.88E-06	34.0
26	**15.4**	**2.31E-06**	**5.39E-06**	1.15E-05		3.25	9.03E-04	1.36E-05	0.4429	6.00E-06	33.4
27	**14.9**	**2.35E-06**	**5.60E-06**	1.19E-05		3.38	9.38E-04	1.39E-05	0.4387	6.12E-06	32.9
28	**14.3**	**2.40E-06**	**5.80E-06**	1.24E-05		3.50	9.72E-04	1.43E-05	0.4347	6.23E-06	32.3
29	**13.8**	**2.44E-06**	**6.01E-06**	1.28E-05		3.63	1.01E-03	1.47E-05	0.4309	6.34E-06	31.8
30	**13.4**	**2.48E-06**	**6.22E-06**	1.32E-05		3.75	1.04E-03	1.51E-05	0.4273	6.45E-06	31.4
31	**12.9**	**2.52E-06**	**6.43E-06**	1.36E-05		3.88	1.08E-03	1.55E-05	0.4238	6.55E-06	30.9
32	**12.5**	**2.56E-06**	**6.63E-06**	1.40E-05		4.00	1.11E-03	1.58E-05	0.4204	6.66E-06	30.5
33	**12.2**	**2.60E-06**	**6.84E-06**	1.44E-05		4.13	1.15E-03	1.62E-05	0.4172	6.76E-06	30.2
34	**11.8**	**2.64E-06**	**7.05E-06**	1.48E-05		4.25	1.18E-03	1.66E-05	0.4141	6.86E-06	29.8
35	**11.5**	**2.68E-06**	**7.26E-06**	1.52E-05		4.38	1.22E-03	1.69E-05	0.4111	6.96E-06	29.5
36	**11.1**	**2.72E-06**	**7.46E-06**	1.55E-05		4.50	1.25E-03	1.73E-05	0.4082	7.06E-06	29.1
37	**10.8**	**2.76E-06**	**7.67E-06**	1.59E-05		4.63	1.28E-03	1.77E-05	0.4055	7.16E-06	28.8
39	**10.3**	**2.83E-06**	**8.08E-06**	1.67E-05		4.88	1.35E-03	1.84E-05	0.4002	7.35E-06	28.3
40	**10.0**	**2.87E-06**	**8.29E-06**	1.70E-05		5.00	1.39E-03	1.87E-05	0.3976	7.44E-06	28.0

Appendix 8

Excel Spreadsheet Laser Hazard Model (2D Q):
DeltaSphere-3000 Modified Configuration (τ=0.8)
Mirror Rotation Rate = **4 rev/sec @ 13.3 samples /degree**

			Laser Hazard Model		for	**DeltaSphere-3000**	**(NIR)**				
			Laser Hazard Model		for	**DeltaSphere-3000**	**(NIR)**				
			r =	**18**	cm						
Wavelength =	**780**	**nm**	**d_{o} =**	**0.25**	**cm**		Valid for R <	882	cm		
Power =	**5.97**	**mw**	**θ =**	**0.5**	**milliradians**						
Mirror Rotation (ω) =	**4**	**rev / sec**	Rotation time =	0.2500	sec						
Sampling =	**13.3**	**sample/degree**	Θ =	1.31E-03		radians					
Limiting Aperture =	0.7	cm	Ω =	5.25E-03		radian/sec					
C_A =	1.445										
Number of Pulses	**R**	**AEL**	**Q_{lim}**	AELx	**T_{lim}**	**t**	**$MPE_{rule\ 1}Cp$**	**$MPE_{rule\ 3}$**	**L**	**α**	α/α_{min}
n	(cm)	(J)	(J)	(J)	(sec)	(sec)	(J/cm^2)	(J/cm^2)	(cm)	(radians)	
	882	**4.220E-07**	1.481E-07	4.22E-07			3.16E-05	1.10E-06	1.0000	1.10E-06	900.0
	700	**5.018E-07**	**2.026E-07**	5.02E-07			3.98E-05	1.30E-06	1.0000	1.30E-06	718.0
1	**533.4**	**6.153E-07**	**2.792E-07**	6.15E-07		0.25	5.22E-05	1.60E-06	1.0000	1.60E-06	551.4
2	**266.7**	**8.701E-07**	**5.039E-07**	8.70E-07		0.50	1.04E-04	2.69E-06	0.8409	2.26E-06	284.7
3	**177.8**	**1.066E-06**	**8.805E-07**	1.07E-06		0.75	1.57E-04	3.64E-06	0.7598	2.77E-06	195.8
4	**133.4**	**1.231E-06**	**1.199E-06**	1.36E-06		1.00	2.09E-04	4.52E-06	0.7071	3.20E-06	151.4

IX. Reference

ANSI Std. Z136.1-2000: for Safe Use of Lasers, Published by the Laser Institute of America.

3rd Tech DeltaSphere-3000 Laser 3D Scene Digitizer User Manual, v2.0, Revision A, 4/13/04

X. Symbols and Abbreviations

A	Area.
AEL	Allowable emission (exposure) limit.
A_{lim}	Area of the limiting aperture.
A_{rect}	Rectangular area.
A_s	Area transmitted through an aperture "s" or arc-chord area.
A_{scan}	Area scanned by the rotating beam in one rotation.
A_τ	Area of the transmitted beam.
A_Δ	Triangular area.
A_φ	Area of the pie shaped wedge.
C	Circumference.
C_A	Wavelength correction coefficient.
C_E	Extended source correction coefficient.
C_p	Pulse correction coefficient.
D	Beam diameter.
d_{lim}	Limiting aperture listed in ANSI Std. Z136.1-2000 (Table 8).
d_o	Exit beam diameter.
$f(\ )$	Function of the argument ().
f_c	Critical frequency, above which ANSI Rule 2 applies for NIR exposures.
FWHM	Full width at half of maximum.
H	Irradiance (watts/cm^2).
h	Height.
L	Distance.
MPE	Maximum permissible exposure
MPE_{CW}	Maximum permissible CW exposure.
MPE_{rule1}	Maximum permissible exposure derived from ANSI Rule 1.
MPE_{rule2}	Maximum permissible exposure derived from ANSI Rule 2.
MPE_{rule3}	Maximum permissible exposure derived from ANSI Rule 3.
n	Number of pulses.
N	Number of samples (Sample Density)
NIR	Near infrared (700 nm < λ < 1050 nm).
NOHD	Nominal ocular hazard distance.
nm	Nanometer.

OD	Optical Density.
OD_{min}	Minimum optical density rating of laser safety eyewear.
PRF	Pulse repetition frequency.
Q	Radiant energy (J).
Q_{lim}	Radiant energy transmitted through the limiting aperture.
Q_s	Radiant energy transmitted through an aperture "s".
r	Distance from laser to rotating mirror.
R	Radial Distance from the rotating mirror.
R_n	The radial distance for "n" pulse periods to sweep across the limiting aperture.
R_{NOHD}	The radial distance equal to the boundary of the ocular hazard zone.
R_X	Extended source to small source crossover distance.
s	Surface aperture or arc
t	Time, pulse width (sec).
t_{FWHM}	Pulse time between the half power points.
T	Time period, such as pulse period, exposure period, etc.
T_{lim}	Time to sweep across the limiting aperture.
w	Beam width.
α	Viewing angle (radians)
α_{min}	Minimum viewing angle (1.5 mr).
Δ	Delta or difference.
θ	Beam divergence (radians).
Φ	Radiant power (watts).
Φ_{avg}	Average radiant power (watts).
$\Phi_{emitted}$	Radiant power of the beam emitted by the scanner.
Φ_{laser}	Radiant power of the embedded laser diode.
φ	Wedge angle.
λ	Laser wavelength.
ω	Mirror rotation rate, vertical scan rate.
Θ	Angular displace, scanner sweep.

Ω	Average scanner sweep rate.
τ	Transmission factor.
1D	One-dimensional.
2D	Two-dimensional.

XI. Distribution

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